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ER-2 Lidar Observations from the October 1986 Fire Cirrus Experiment

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1988

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ER-2 LIDAR OBSERVATIONS

from the October 1986 FIRE Cirrus Experiment

by:

James D. Spinhirne*, Dennis L. Hlavka, and William D. Hart****

I. SUMMARY:

A description of the Cloud and Aerosol Lidar (CALS) data characteristics, and available products, plus flight times and locations are presented for the FIRE cirrus experiment of October 13 through November 2, 1986.

II. INTRODUCTION:

A field experiment was conducted in Wisconsin during October 1986 as part of the First ISCCP (International Satellite Cloud Climatology Project) Regional Experiment (FIRE). The CALS airborne lidar was flown for this experiment on the NASA ER-2 high altitude aircraft. The primary objectives of the CALS observations were to intensively measure cirrus cloud top height and structure for basic cirrus studies and for validation of satellite cloud retrievals.

III. DESCRIPTION OF LIDAR RETURN SIGNAL:

Lidar data is segmented according to ER-2 flight lines. A flight line consists of a straight line segment usually 5 to 15 minutes in length. Lidar pulse firings (shots) are taken in the nadir direction at 5.00 Hz or approximately every 41 meters along the flight line. Each backscatter signal is sensed 2850 times at 7.5 meters vertical resolution. Signals for polarizations both parallel and perpendicular to the transmitted laser pulse are acquired. Each recorded lidar signal is composed of two basic components: the actual lidar signal due to backscattering from the laser pulse and a background signal arising from scattering of ambient light into the receiver field of view.

The fundamental physical measurement derived from CALS data is the total attenuated backscatter coefficient of the atmospheric constituents residing in a column below the aircraft. The signal is given by the lidar return equation:

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$$P(Z)=\{[KEB(Z)T(Z)^2]/Z^2\}+P_B$$

where

$P(Z)$ is the total power measured by the lidar receiver resulting from the backscatter at a distance Z from the instrument, E is the energy contained in a given laser pulse, K is a system calibration constant, $B(Z)$ is the total backscatter coefficient, $T(Z)$ is the transmission factor, Z is distance from the instrument to a given point, and P_B is background signal resulting from sunlight scattered into lidar receiver sensor.

Combining the factors $B(Z)$ and $T(Z)^2$ into a single term defines the attenuated backscatter coefficient,

$$B'(Z)=B(Z)T(Z)^2.$$

We can now write the lidar equation as

$$P(Z)=[KEB'(Z)/Z^2]+P_B.$$

Since the power detected by the lidar sensor, $P(Z)$, is recorded as a function of time, $B'(Z)$ as a function of time is retrieved from the data by solving the equation:

$$B'(Z)=[(P(Z)-P_B)Z^2]/[KE].$$

The background signal P_B is given by:

$$P_B(\lambda o) = I_B(\lambda\ o)A\ \Omega\Delta\lambda$$

where A is the receiver area, I_B is the intensity of the background radiation, Ω is the solid angle of the receiver field of view, and $\Delta\lambda$ is the system wavelength bandwidth. The background radiation is an important factor since measurements are typically made in the daytime and the background can add significantly to signal noise. Also, due to large changes of albedo for cloud and surface areas over which the aircraft flies, the background introduces a variable offset to the data that must be removed.

The accuracy of cloud measurements is limited by the inherent signal noise which is a function of the square root of the total detector current during a sample interval. The signal to noise ratio (S/N) is represented as:

$$S/N = i_s/[2\Delta fe(i_s+i_b)]^{1/2},$$

where i_s is the detector current produced by the backscattered signal, i_b is the detector current produced by background ambient light, Δf is the system electronic bandwidth and e is electron charge. The signal noise defines the range to which the lidar data may be usefully applied.

Usable signals may be obtained through an extended vertical depth in the case of some cirrus clouds. If the attenuation is relatively small, the S/N ratio may remain high enough for detection of the cloud base. However, for more dense clouds the discernible signal range, or the range where the signal falls to the noise level, may be much less than the physical depth of the cloud.

The linear depolarization ratio of the return signal is another parameter derived from the CALS observations. The ratio indicates water/ice phases of cloud particles, since the single scatter linear depolarization for spherical water drops is zero. For ice particles the depolarization may be quite high, depending on the size and shape of the particles. Complications arise due to the multiple scattering which occurs in the more dense clouds, and increasingly non-zero values of linear signal depolarization will be observed with range.

To obtain the linear depolarization ratio for the backscatter, the lidar signal is detected through polarizers aligned parallel and perpendicular to the polarization plane of the transmitted laser pulse. If the depolarizing influence of multiple scattering is neglected, the linear depolarization ratio δ of the backscattered signal is defined as

$$\delta = K_p P_s / K_s P_p$$

where the term K_p/K_s accounts for the relative response of the receiver for the two orthogonal polarizations, P_s is the perpendicular component of the signal and P_p is the parallel component.

IV. CALS CALIBRATIONS:

A. Determination of the System Calibration Constant:

Inspection of the lidar equation reveals the need to know a system calibration constant K in order to retrieve the backscatter coefficient from the data. The value of K is dependent upon many factors concerning the physical, optical, and electronic make-up of the instrument and is not easily determined directly. To bypass this problem, we use a portion of the total lidar signal to find the value of the calibration constant.

If we solve the lidar equation for K we have

$$K=[(P(Z)-P_B)Z^2]/[EB'(Z)].$$

We see that K can be determined from the signal if we know the values of the variables on the right side of the equation. P(Z) is measured and E is obtained by sampling and recording the laser pulse as it exits the instrument. The background signal P_B can be determined if the scattered laser energy is not making a contribution to the total measured signal. In the case of the CALS, the signal is recorded for a period of time after the pulse has encountered the ground. Consequently, an average of the signal samples from the below ground portion of the record is used as the background signal.

The calibration constant may be determined from a known backscatter cross section. A known cross section is possible for the CALS since it is at high altitude where the following two assumptions can be made with some degree of reliability:

1) The atmospheric scattering in the stratosphere above all of the cloud layers is due to molecular components and no significant aerosols or absorbing gases are present.

2) The upper atmosphere is horizontally homogeneous and K is constant with time.

The first assumption permits us to calculate the attenuated backscatter based upon the vertical atmospheric profile determined from upper air soundings. From the modeled B' all of the necessary factors are known to calculate values of K from the lidar equation. In order to minimize the effects of noise and arrive at a value which can be used for a given ER-2 flight, K is determined through a vertical segment of the upper atmosphere for each lidar shot. Then, by using assumption 2, the calibration values from a large number of shots are averaged to produce a final value.

B. Determination of Depolarization Ratio Calibration:

The relative response between the parallel and perpendicular channels of the lidar receiver needs to be known in order to calculate the depolarization. The factor is calculated from test firings of the CALS during which a half wave plate rotating the beam polarization 45 degrees has been installed. The ratio of the perpendicular response to the parallel response while the half wave plate is installed gives the calibration factor.

V. DESCRIPTION OF DATA PRODUCTS:

Four basic Lidar products are available from the field experiment:

a) Quick-look gray scale prints

b) Cloud top height files on computer compatable tapes (CCT's)

c) Attenuated backscatter CCT files

d) Return signal, attenuated backscatter, and depolarization ratio color prints

A. Quick-Look Prints:

Quick-look data images are the first product produced after a flight. They consist of gray-scale strip

charts of the log of the raw lidar return signals - one chart per flight line. The y - axis is height (measured in kilometers) while the x - axis is time of return signal (measured in GMT). The cloud height measurement indicated by the charts is an approximation of the true height since a constant aircraft height of 19.2 kilometers is assumed rather then the true slowly fluctuating aircraft height. Height errors of up to 400 meters could be possible in the quick-look presentations. The time code indicates the time at the beginning of time code boxes. Quick-looks for the experiment are contained in this document in Section VI.

B. Cloud Top Height CCT's:

Cloud top height CCT's are to be made available through the NASA Climate Data System (NCDS). Each data record contains aircraft data such as latitude and longitude and is a function of time. Each tape file corresponds to a single ER-2 flight segment. A flight segment is defined as the interval between the time the ER-2 pilot switches the laser on to the time he switches it off.

In principle the cloud top height may be determined from the discontinuity of the scattered lidar signal at a cloud top. On a shot by shot basis however, a simple constant threshold for cloud detection is beset with problems since the return from thin clouds may be similar in intensity to noise fluctuations of the signal. A special filtering algorithm of the data was developed to help eliminate this problem. The detection algorithm applies a sequence of cloud top detection trials. First, a coarse search for clouds takes place on a highly filtered shot profile. If a signal return is found above a defined threshold value (the threshold is a function of the background offset signal and thus noise level), then the search backs up a specified increment and searches the highly filtered data for two back-to-back signal values above the same threshold. At this point, if a cloud is detected, the search backs up again to analyze every data point in the interval enveloping the height where the cloud was detected, and the initial cloud return "spike" is found in order to accurately locate the cloud top. In this manner, both detection of thin clouds and more accurate top height for dense clouds is obtained. Correction for the true aircraft altitude from aircraft pressure altitude and correction for pitch and roll are also applied. Absolute cloud height resolution will be less than 15 meters for dense clouds. The minimum scattering discontinuity at which a thin cloud may be detected is approximately at a backscatter cross section five times above molecular scattering. However, for very thin clouds the height detection still does not acquire all cloud tops. The height determination algorithm for a diffuse extended cloud layer will typically find the cloud height as a distribution of values through the layer.

The cloud top height CCT's also contain ground return information. The ground return (or ground reflection of the laser pulse) can only be seen in those lidar shot profiles where no clouds exist or existing clouds are sufficiently thin optically that enough of the laser pulse reaches the ground to produce a detectable signal spike. The ground return height is an accurate measure of the height of the earth's surface above sea level.

C. Attenuated Backscatter CCT's:

Tape files may be written which consist of a set of vertical profiles giving attenuated backscatter derived from the lidar. These tapes will be provided on a request basis only.

Tape Structure:

The data are formatted into tape files. Each file corresponds to an ER-2 flight segment.

Data Structure:

Each file is comprised of a set of physical records. Each physical record on the tape corresponds to a single CALS lidar shot. The data records have two logical sections. The first section, which contains 32 bytes, holds timing, location, and other data information. The second section, the data portion, holds the attenuated backscatter coefficient values for a given lidar shot. The backscatter is stored in a array of values, the number of which depends on the thickness of the sampled layer. The vertical distance between each of these samples is a known constant height range which may be greater than 7.5 m depending on the given data application. The length of the second logical section depends upon the number of data samples which are included in the record.

To obtain widespread computer readability, all values are recorded as positive, four byte, binary integers. To return the values to usable quantities, a conversion operation must be performed on each. The conversion formulas are supplied with each tape.

D. Signal Intensity and Depolarization Ratio Color Prints:

Available upon request on a limited basis only, the prints image a four minute or greater segment of a flight line showing color coded values of the observed backscatter or depolarization ratio. The computing algorithm for depolarization accepts only return signal strengths above a set threshold. Ratios falling outside these constraints are set to zero. As a result, only valid cloud depolarization ratios are displayed.

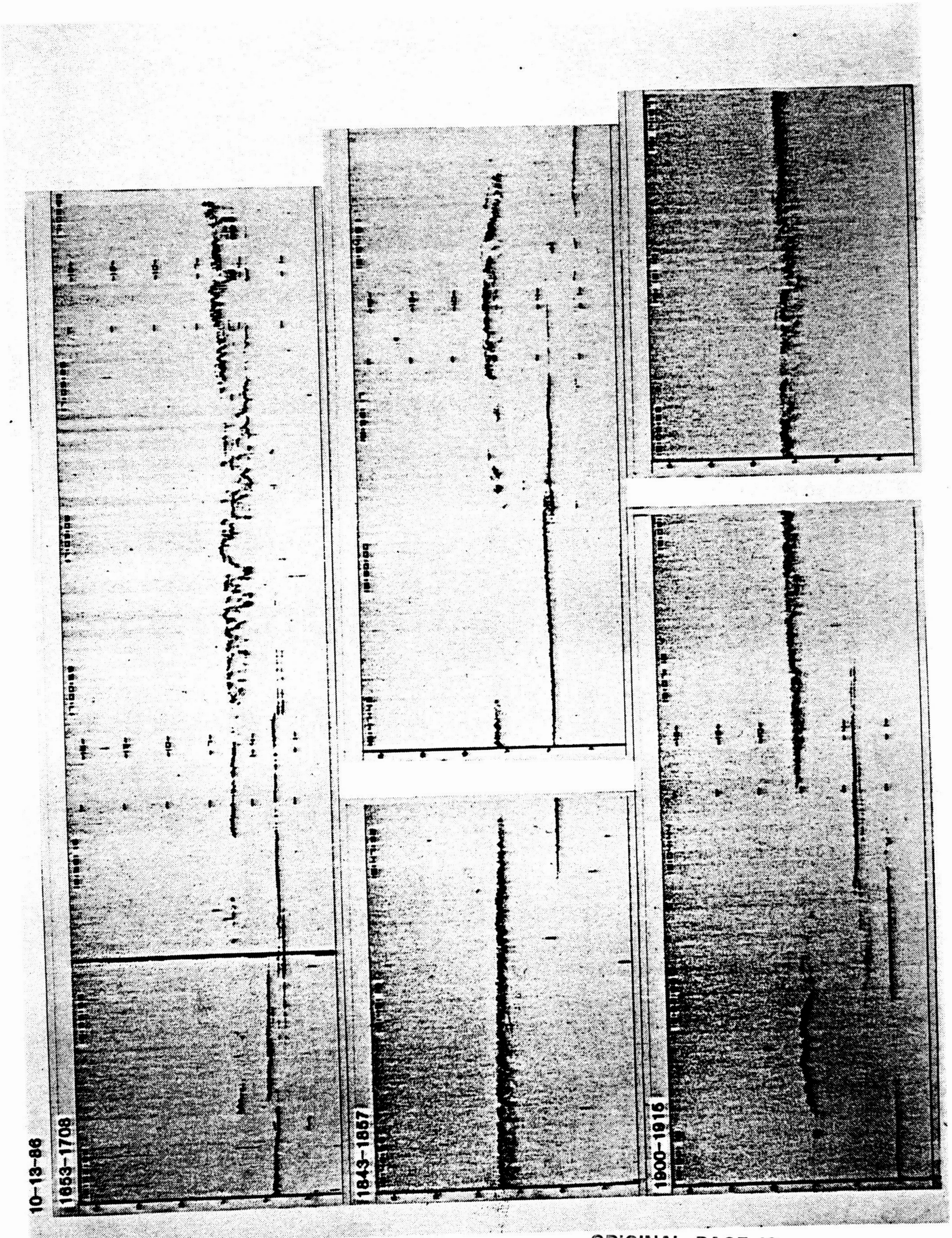
VI. DESCRIPTION OF FLIGHT DAYS:

This section displays all quick-look data images available during the experiment, showing flight line start and end times and general cloud structures. Also displayed are location maps for each flight line. The following eleven days make up the experiment dataset:

1) October 13, 1986
2) October 15, 1986
3) October 19, 1986
4) October 21, 1986
5) October 22, 1986
6) October 24, 1986
7) October 27, 1986
8) October 28, 1986
9) October 30, 1986
10) October 31, 1986
11) November 2, 1986

A. Quick-Look Prints:

The following quick-look prints show date, start time, end time, and general cloud features of all available flight lines for the eleven dates covered: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1843-1857
1900-1916

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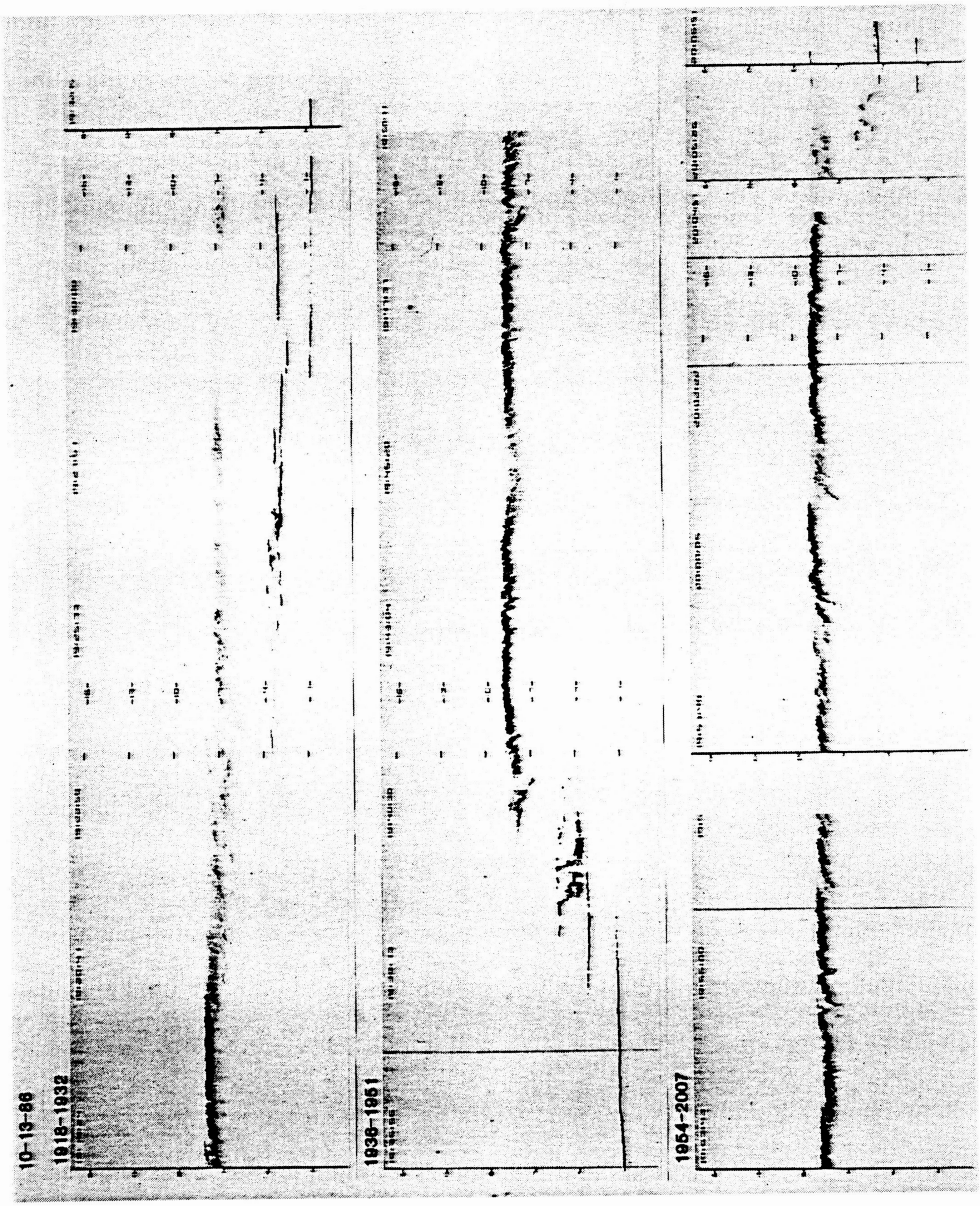

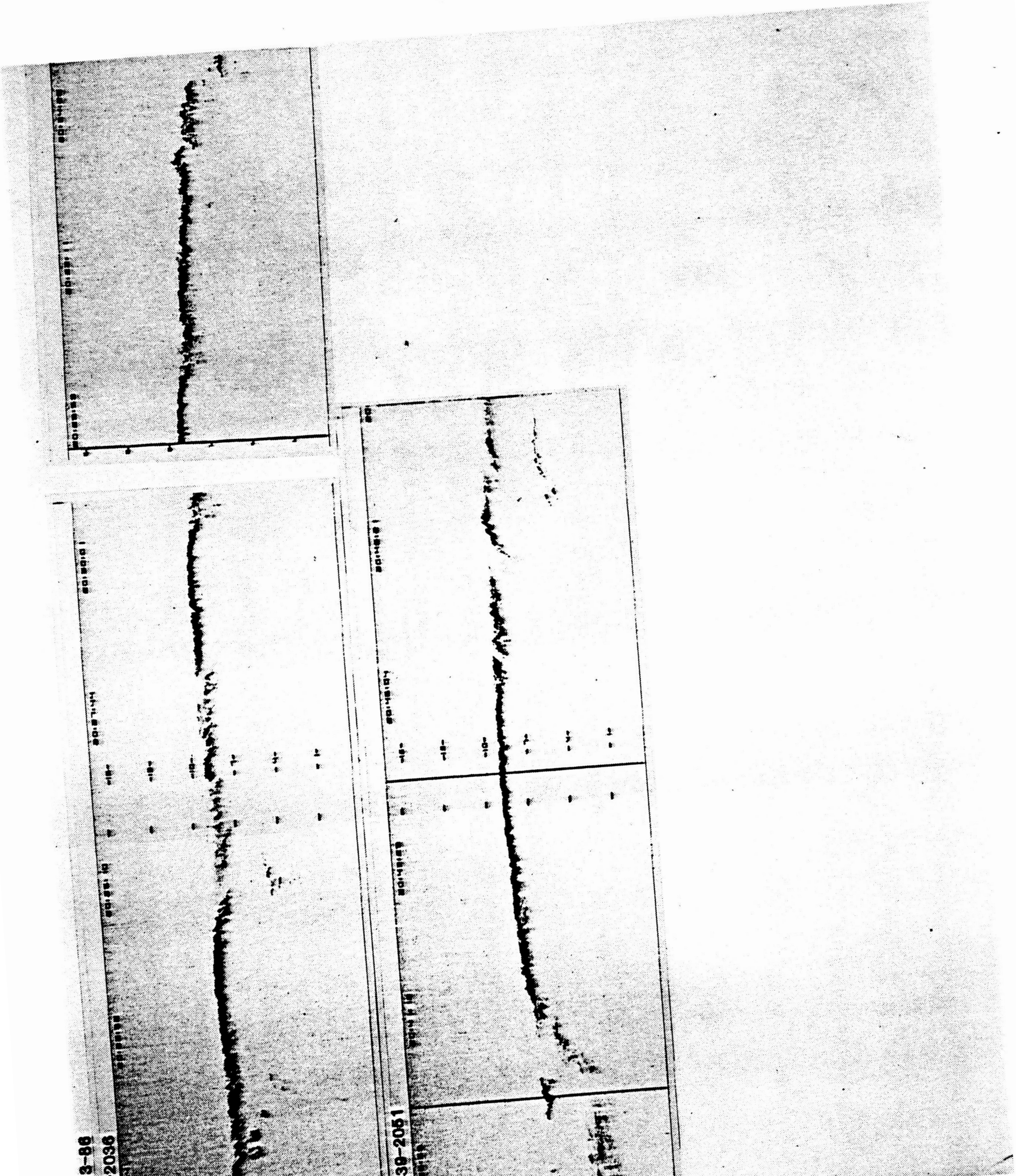
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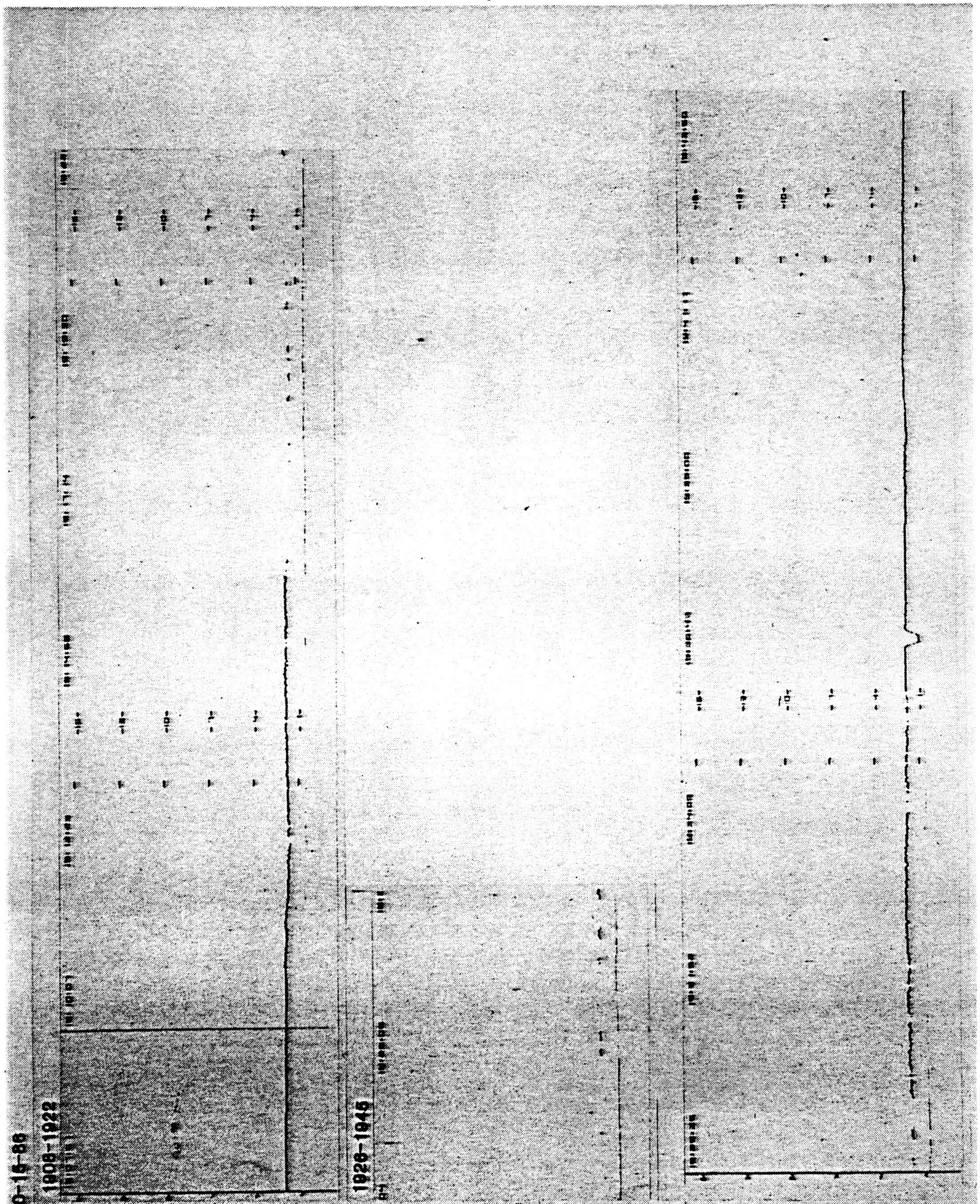
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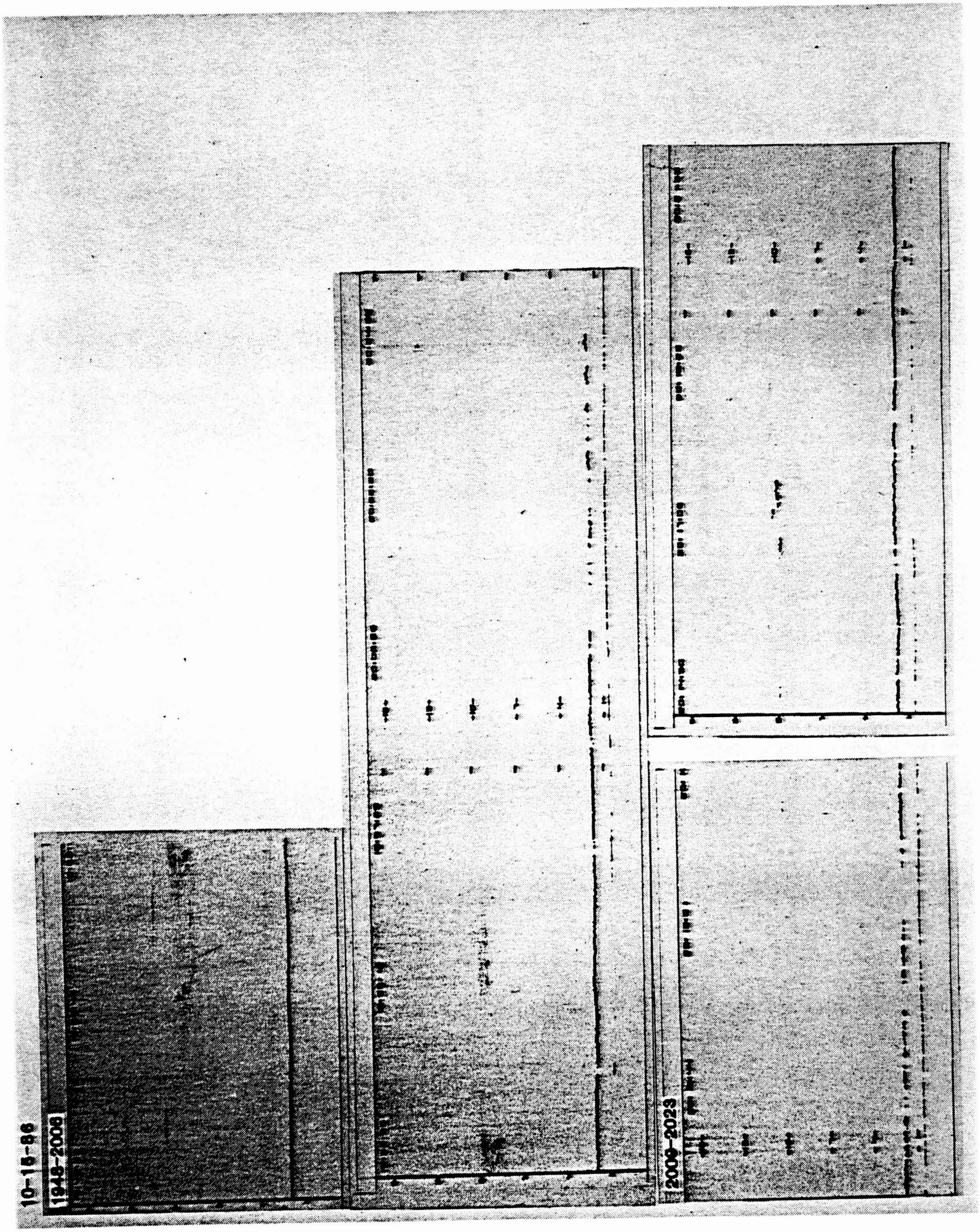
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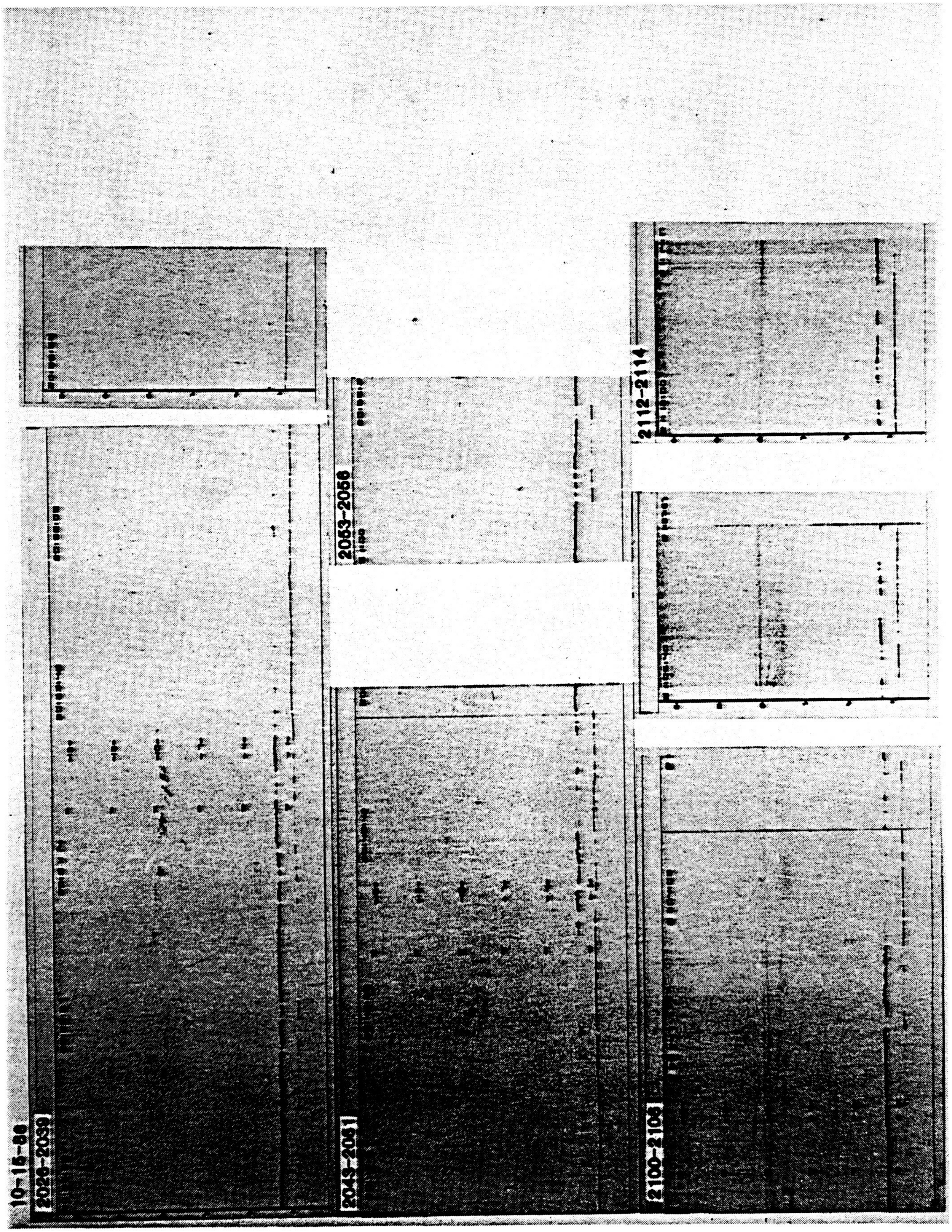

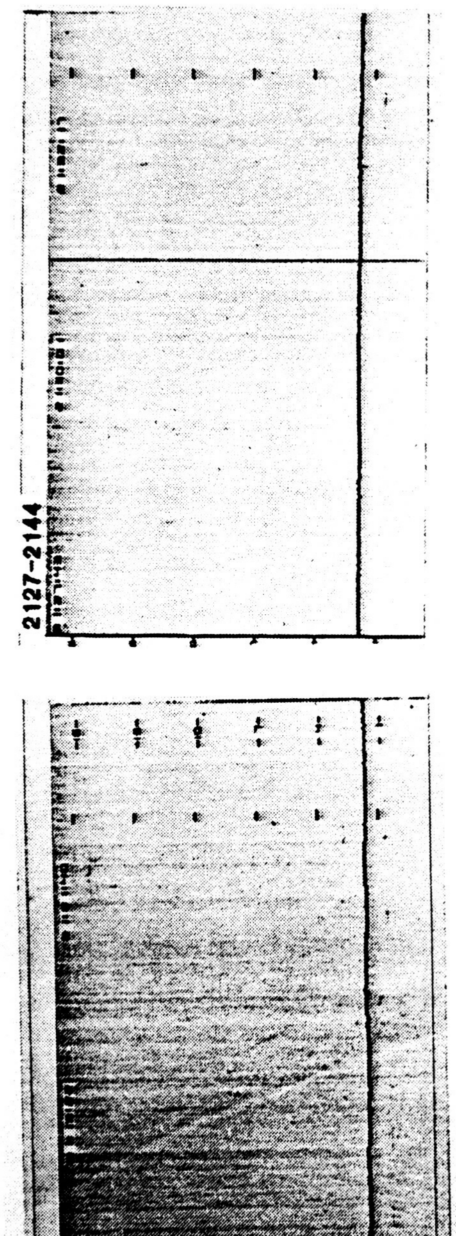
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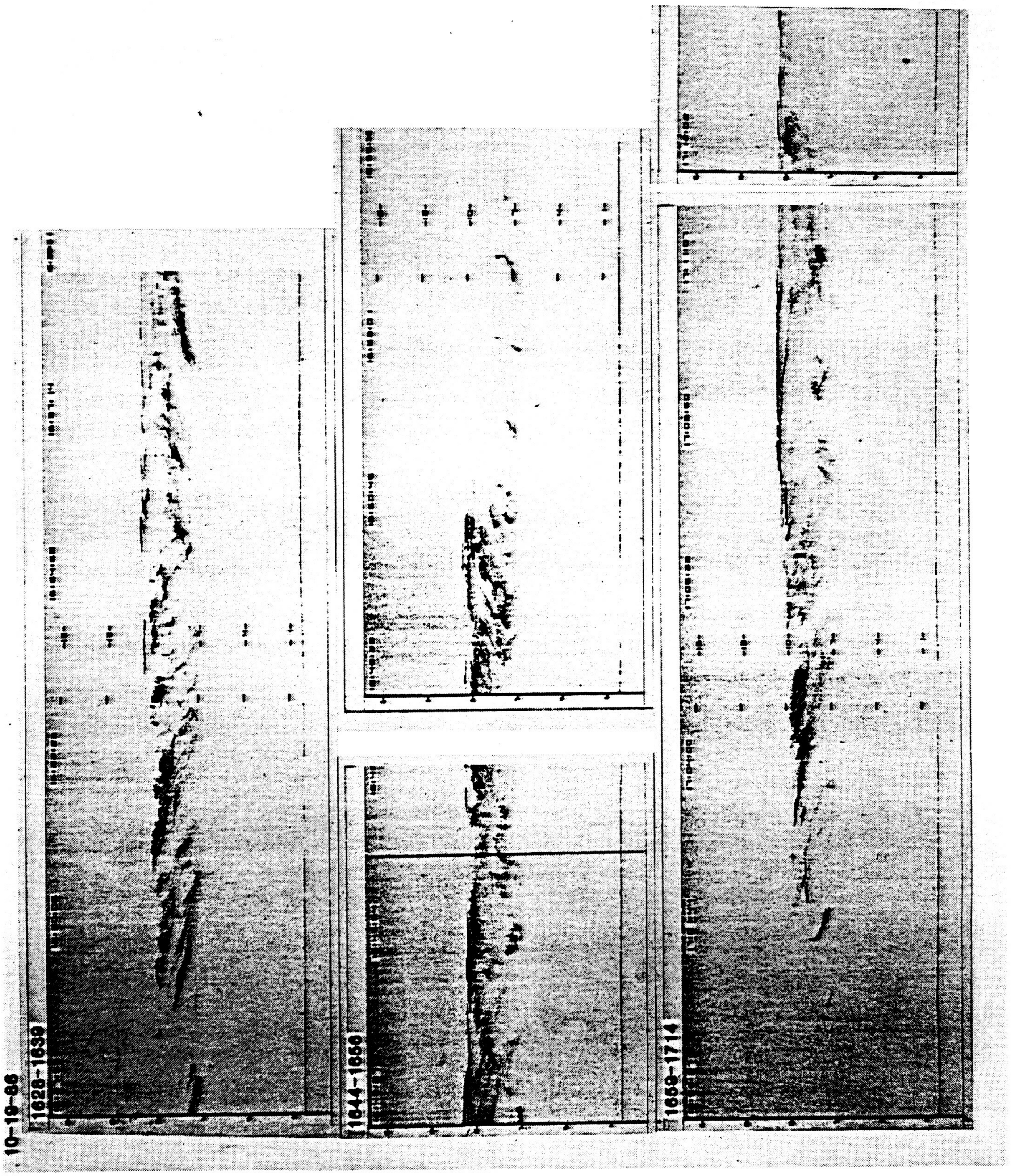
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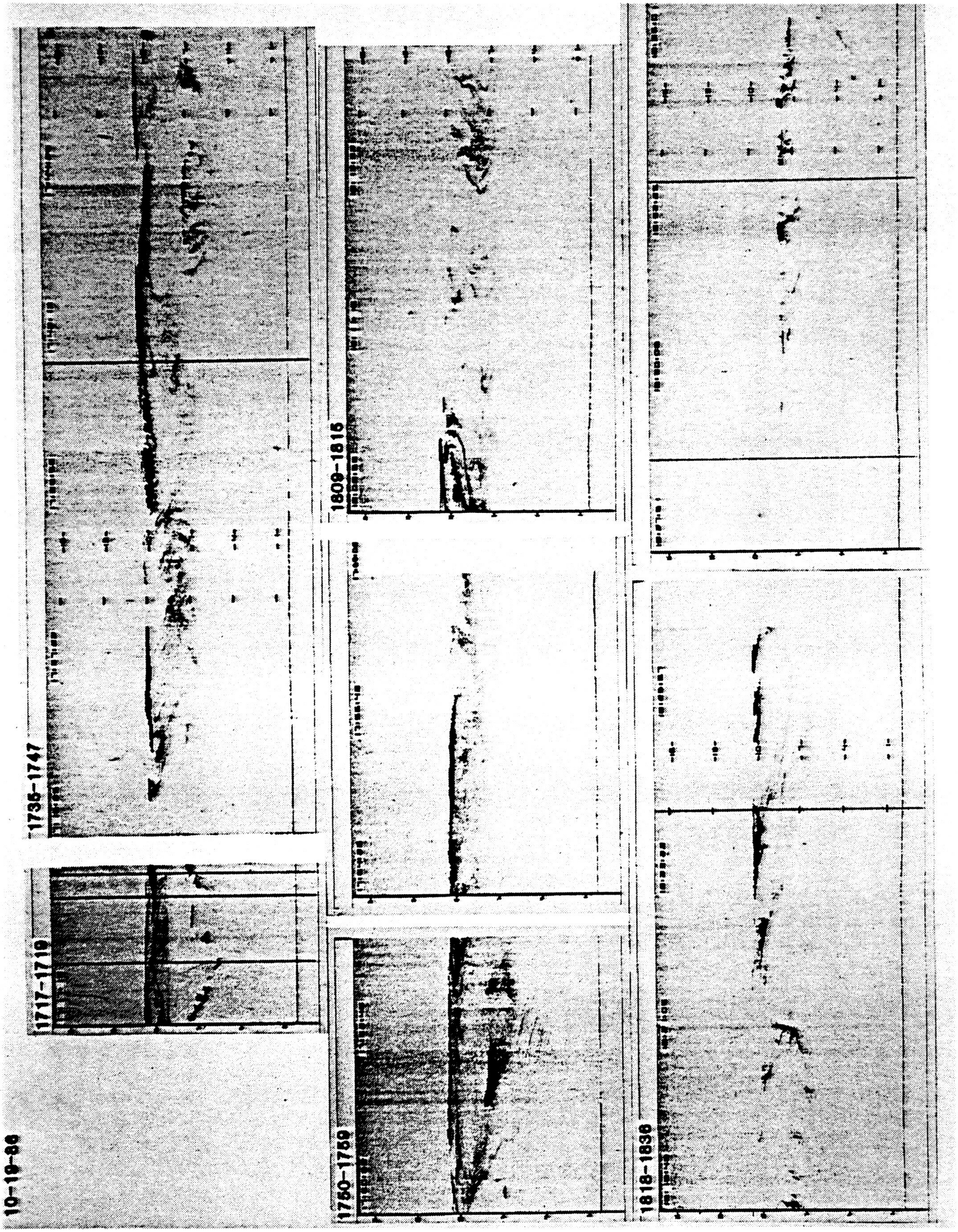
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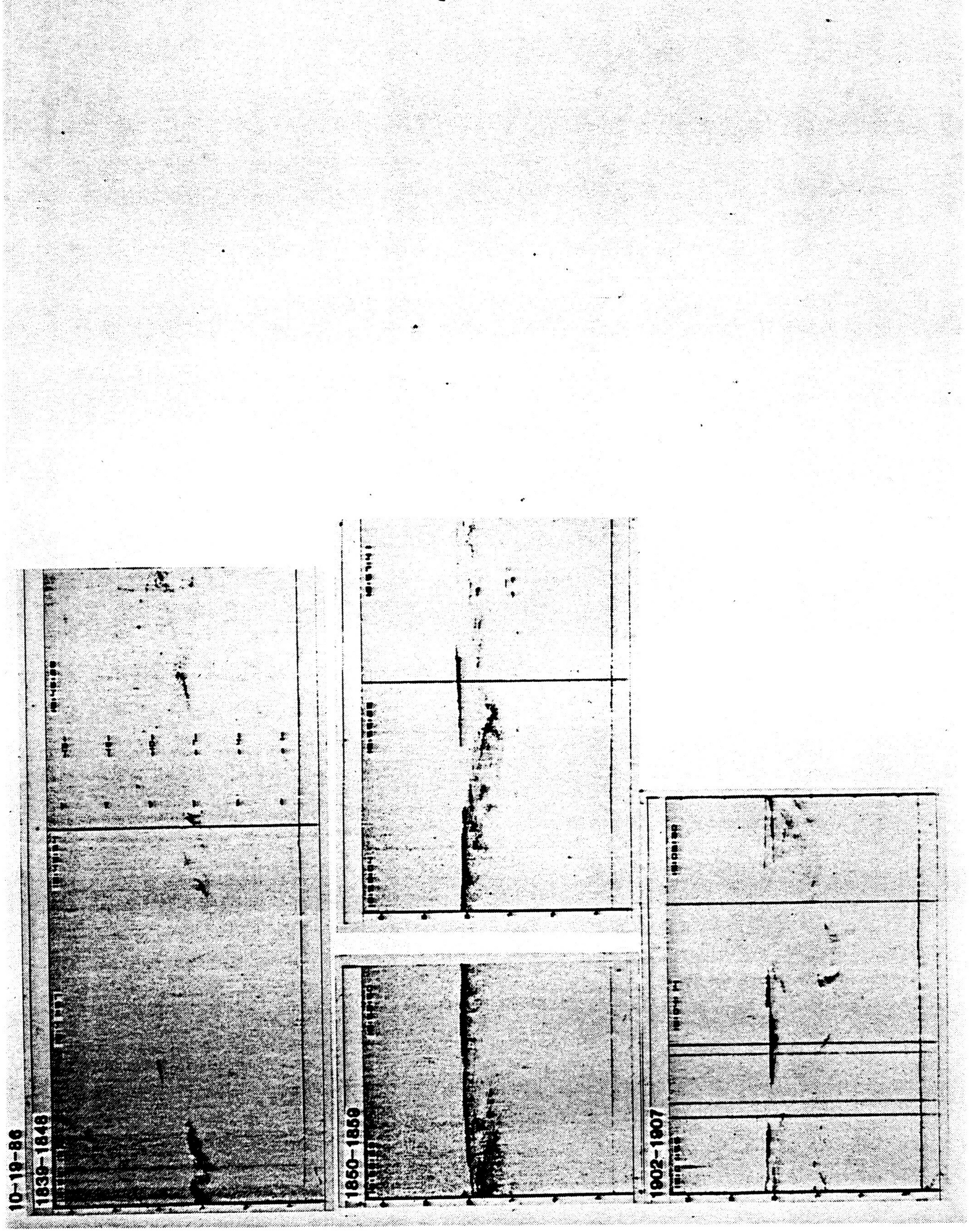
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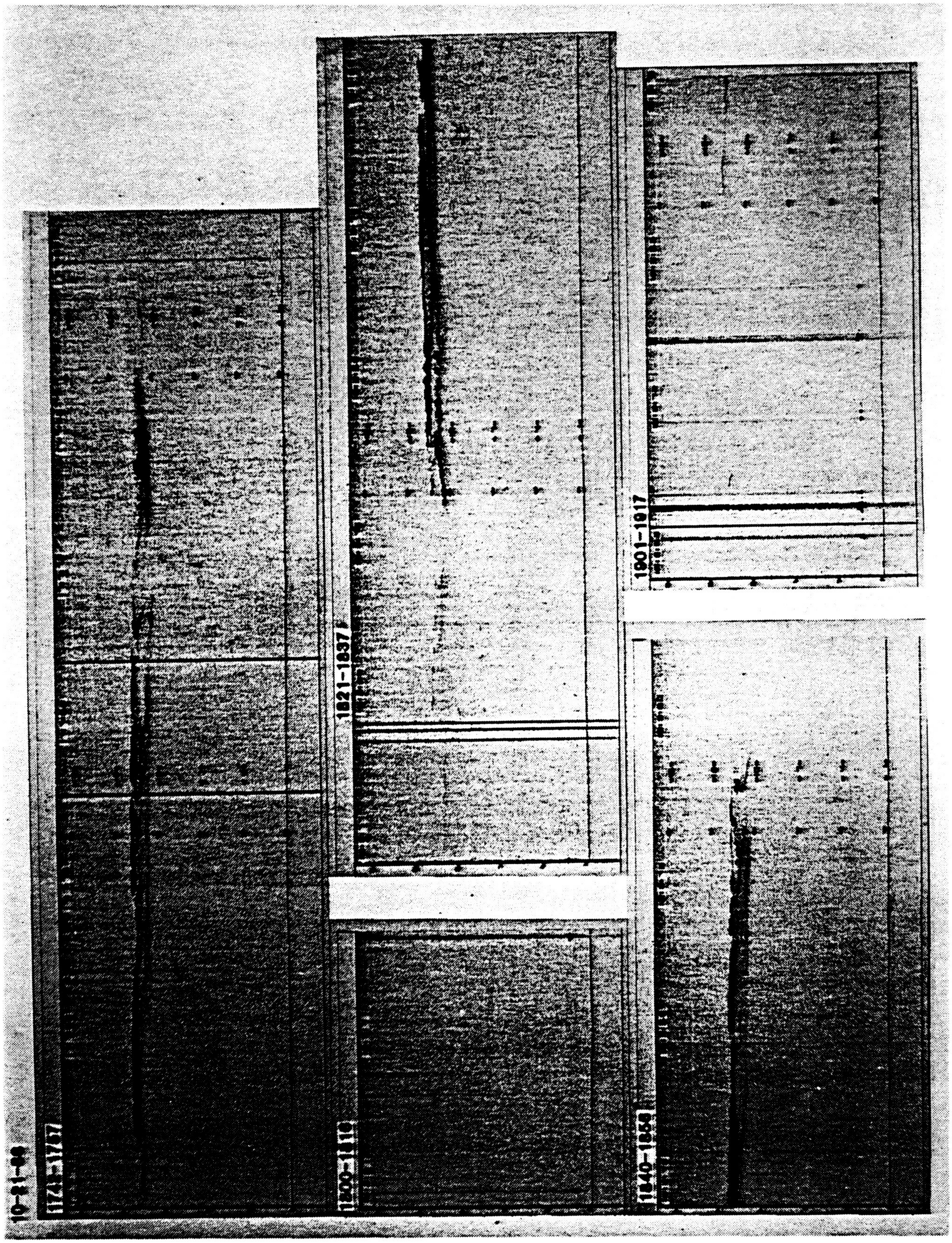
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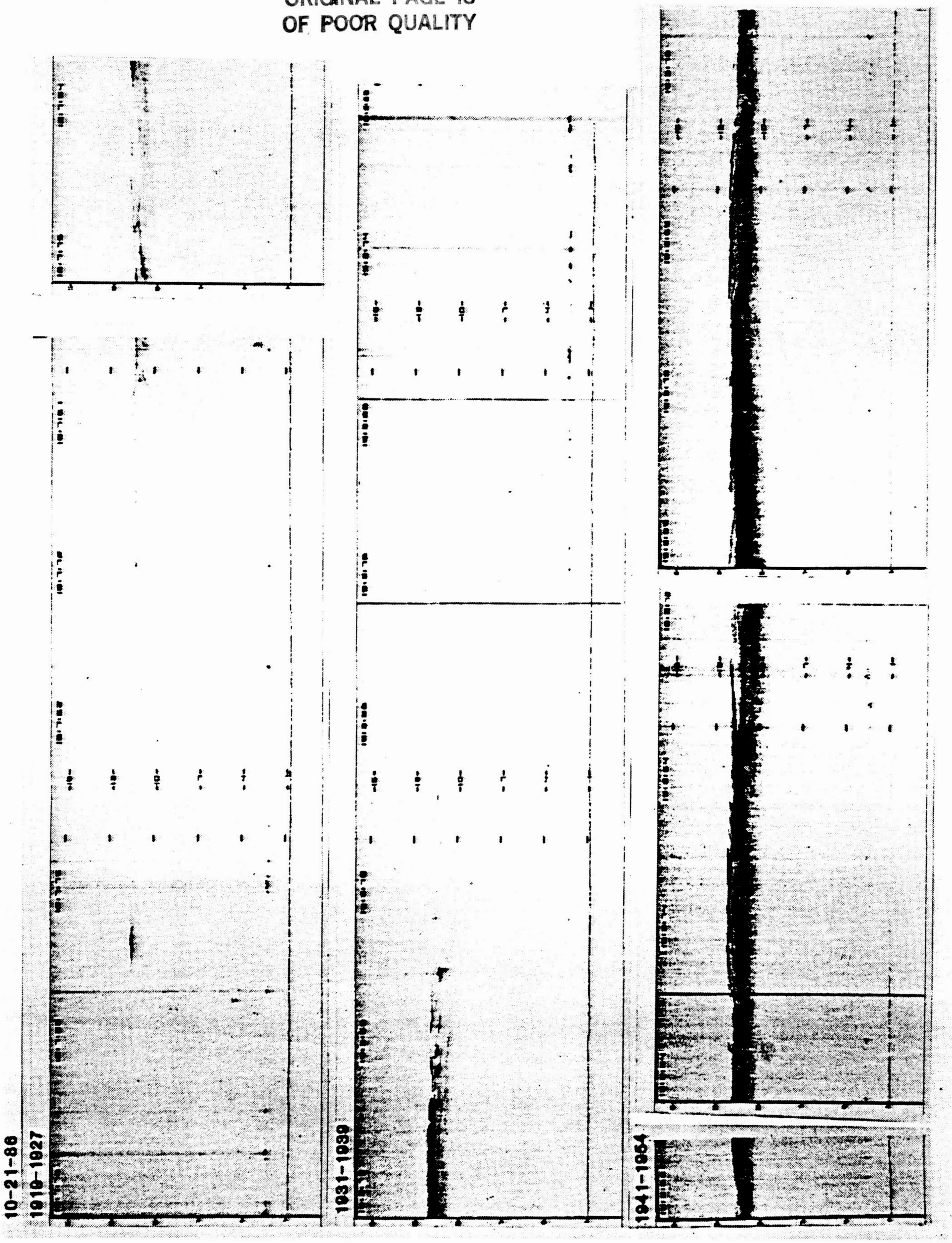

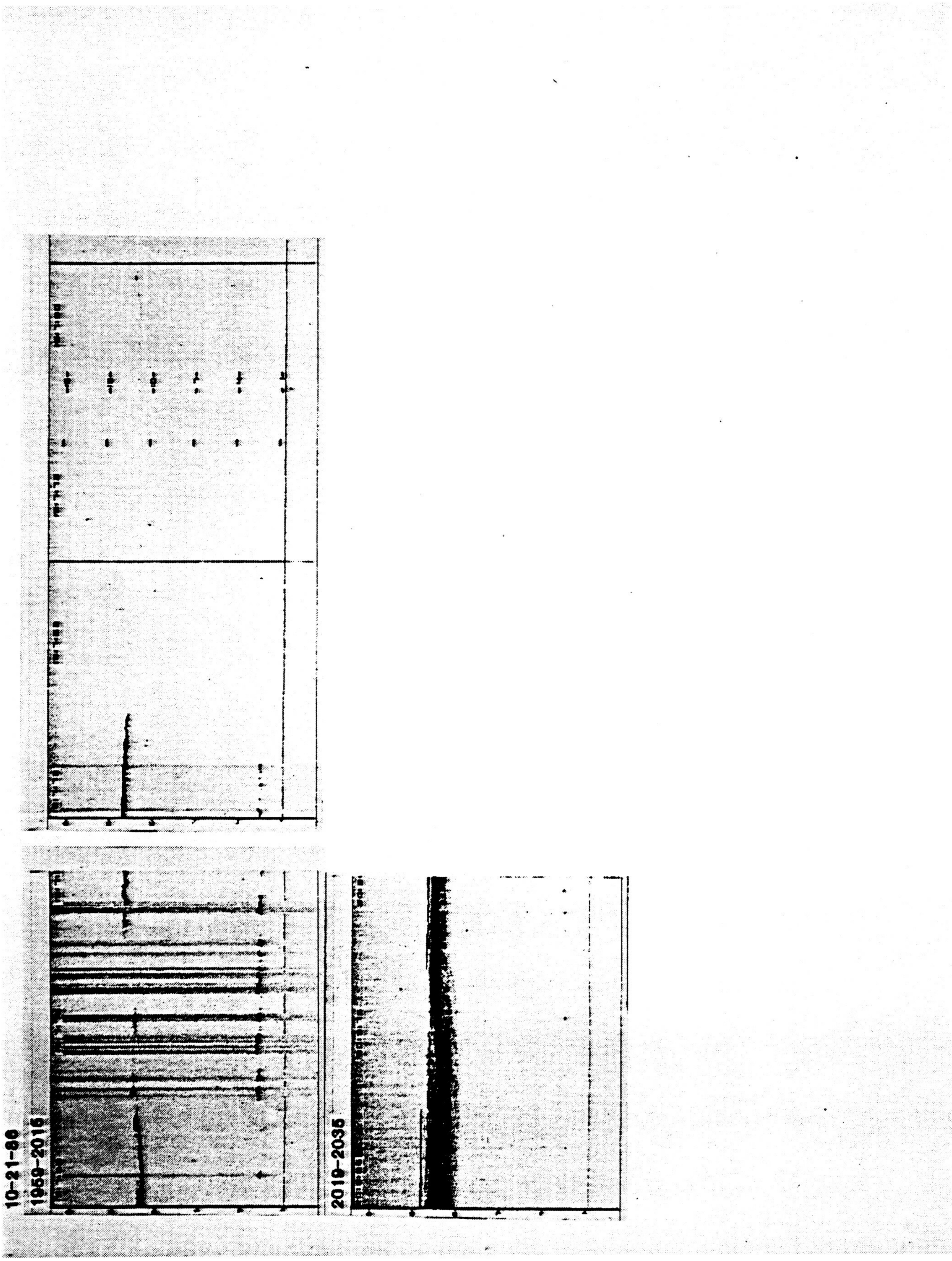
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2019-2035

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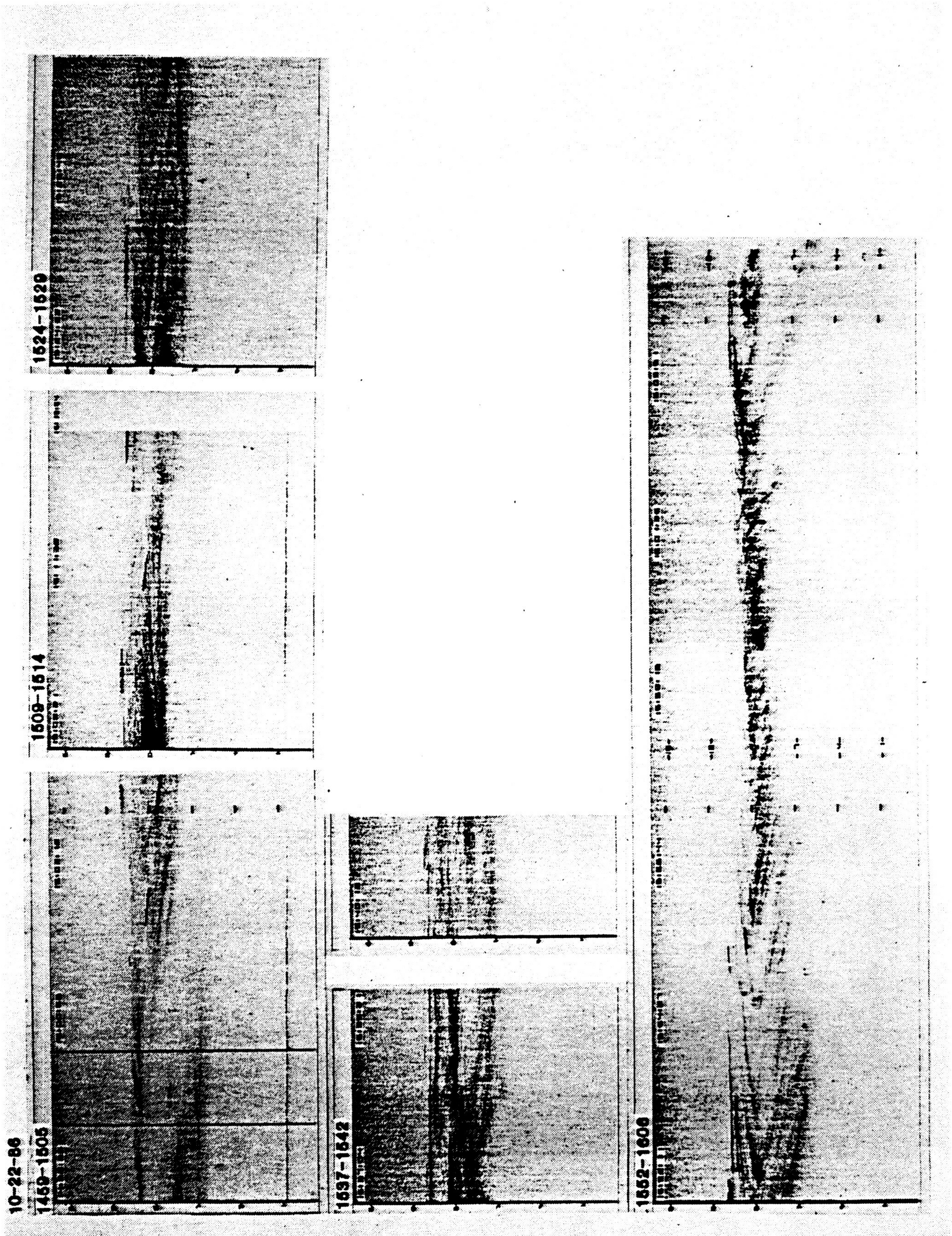

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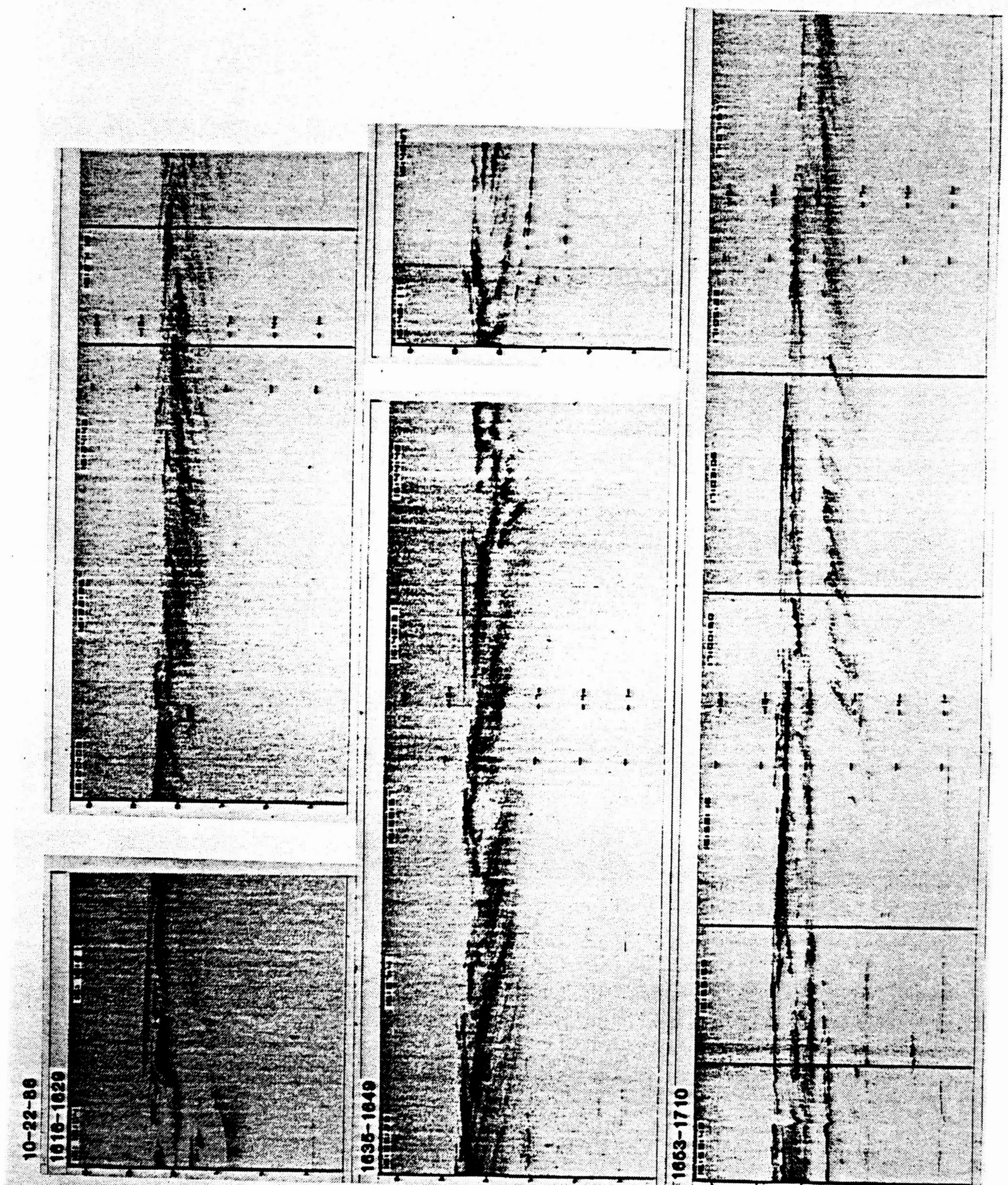

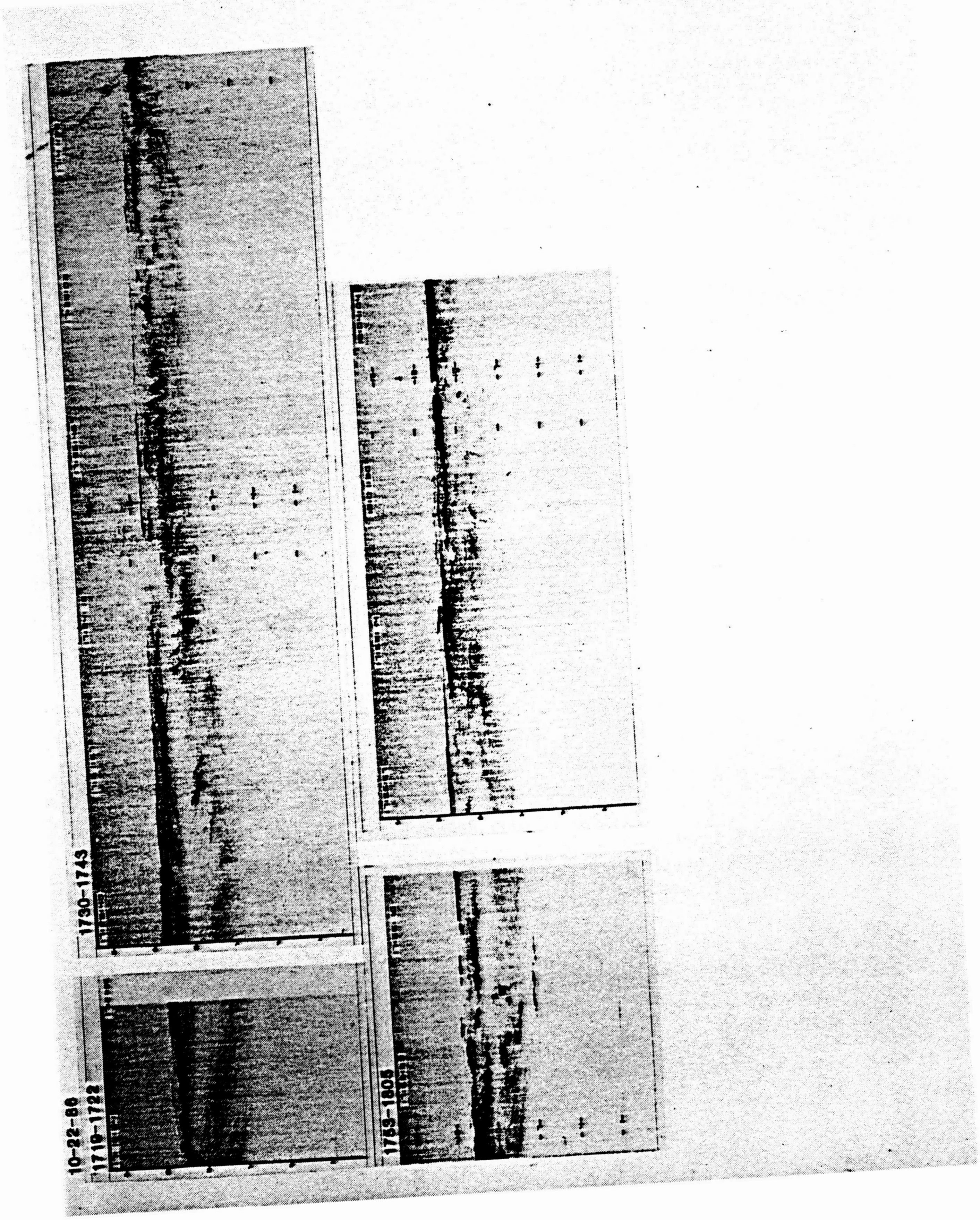
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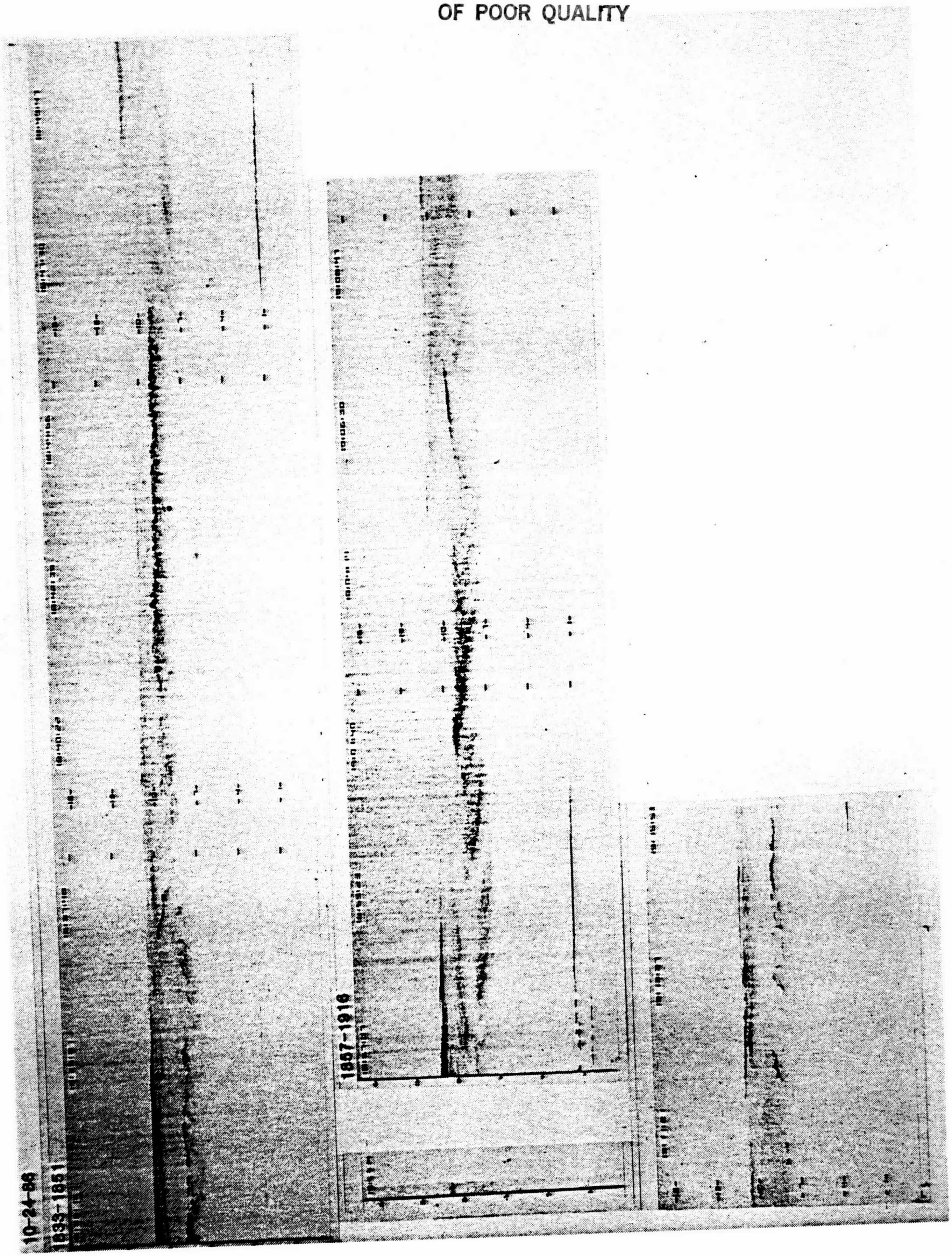
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1857-1916

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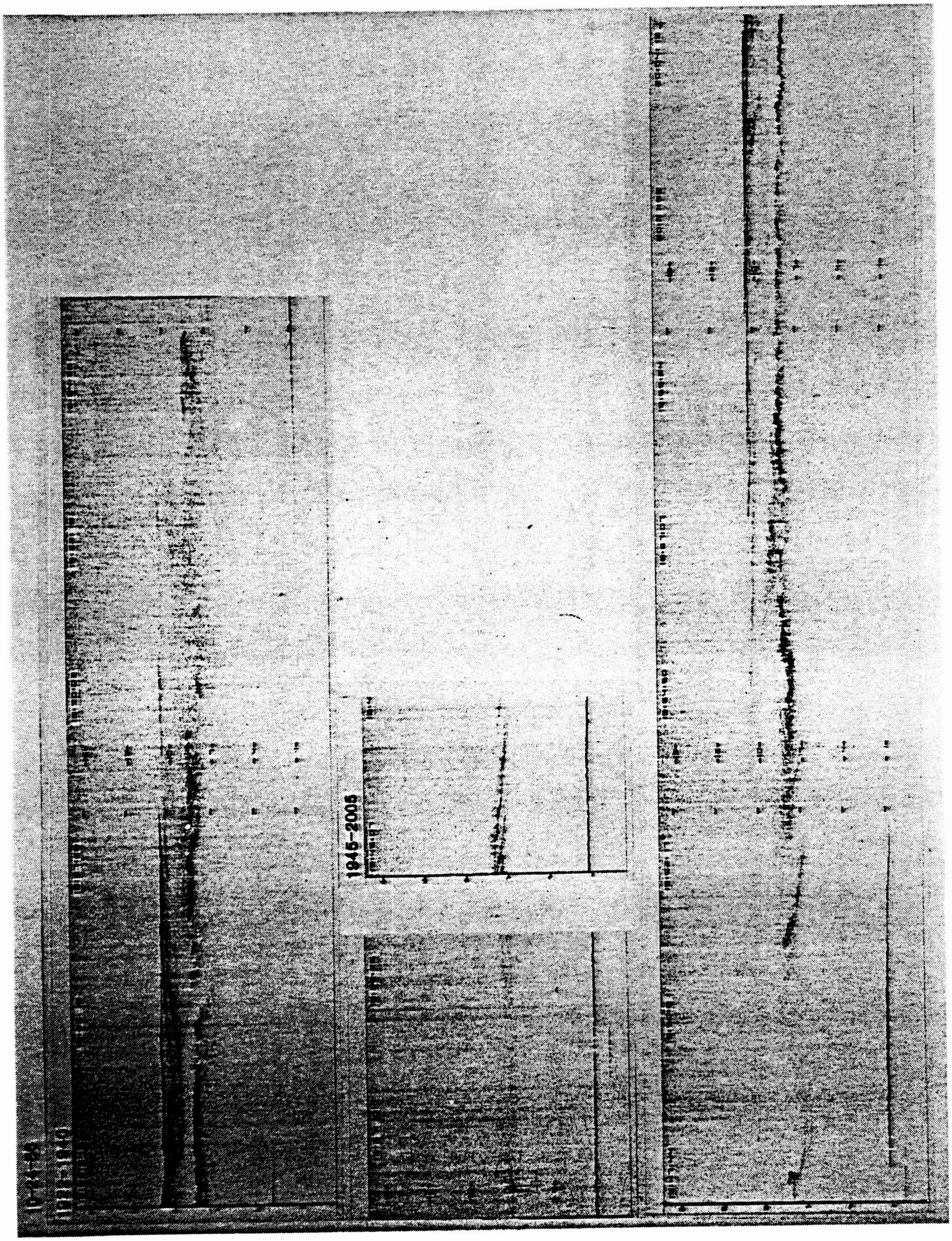

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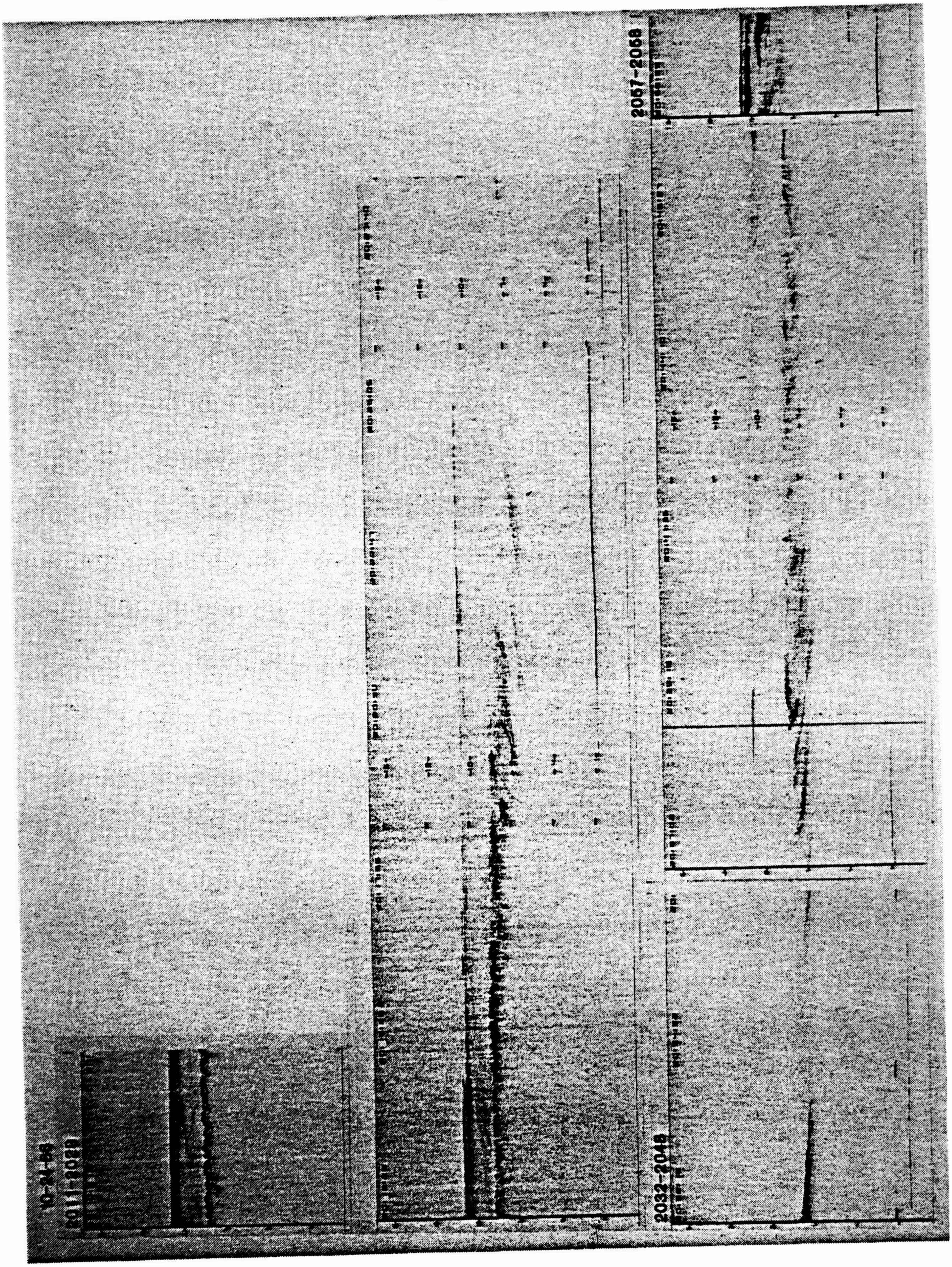

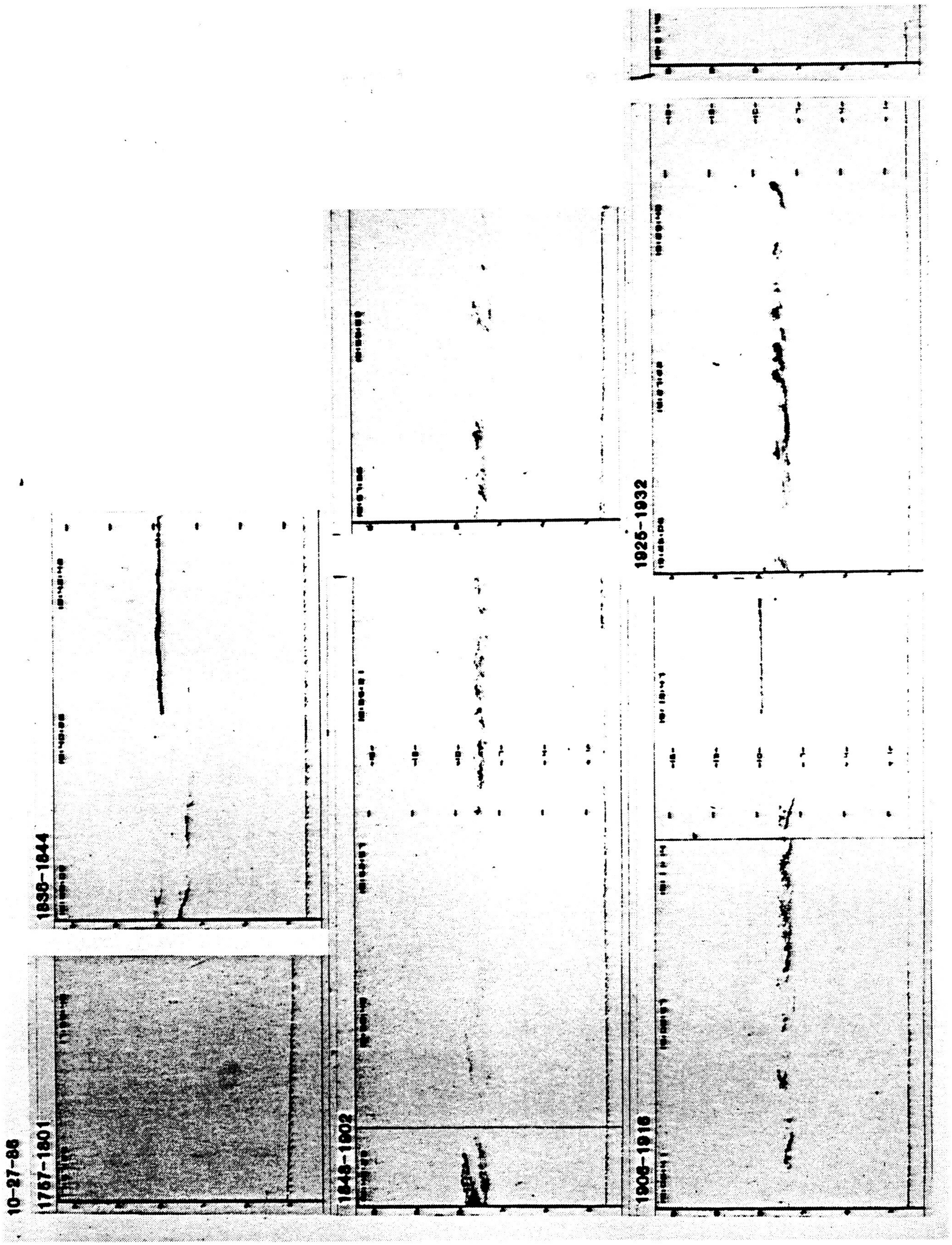
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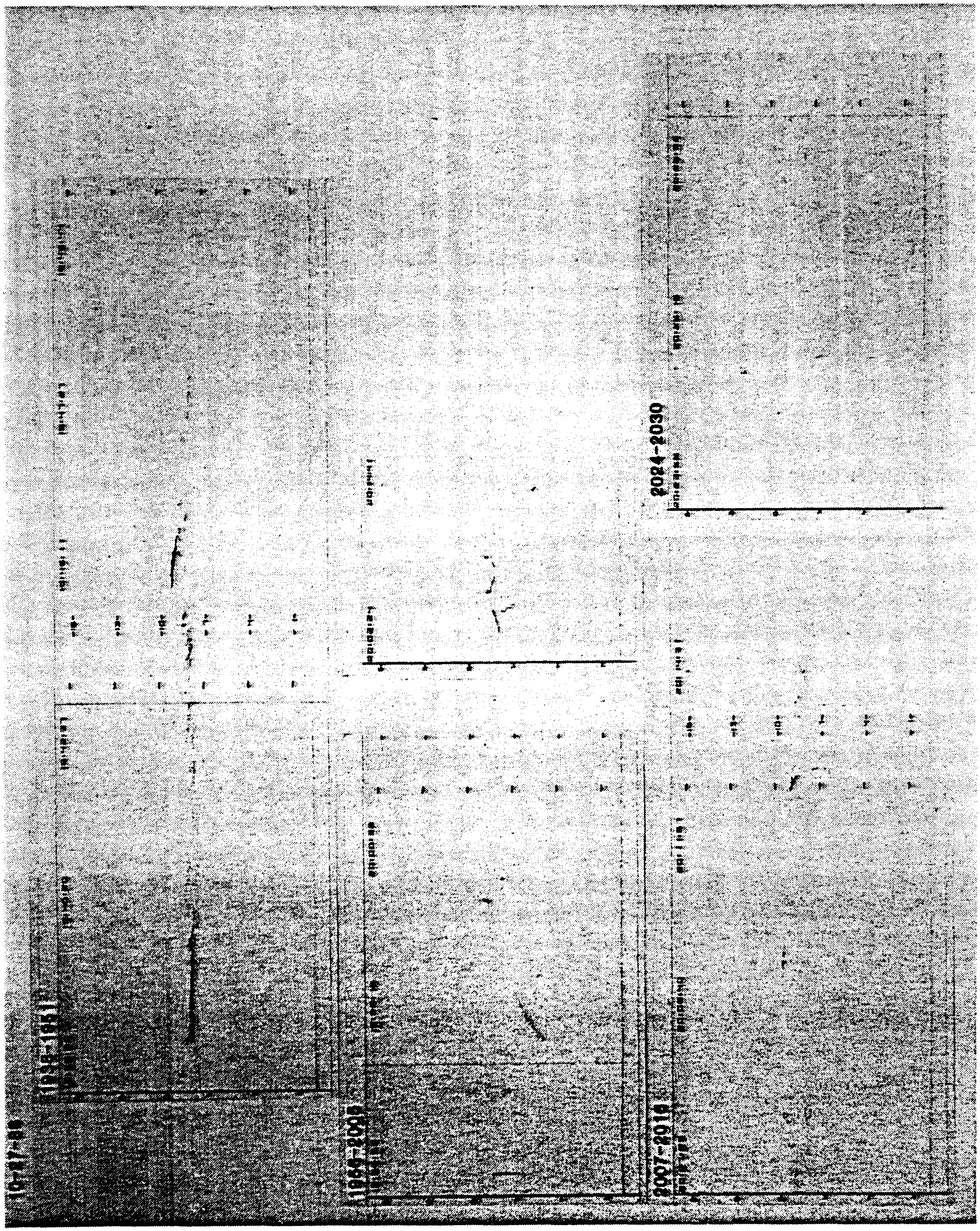

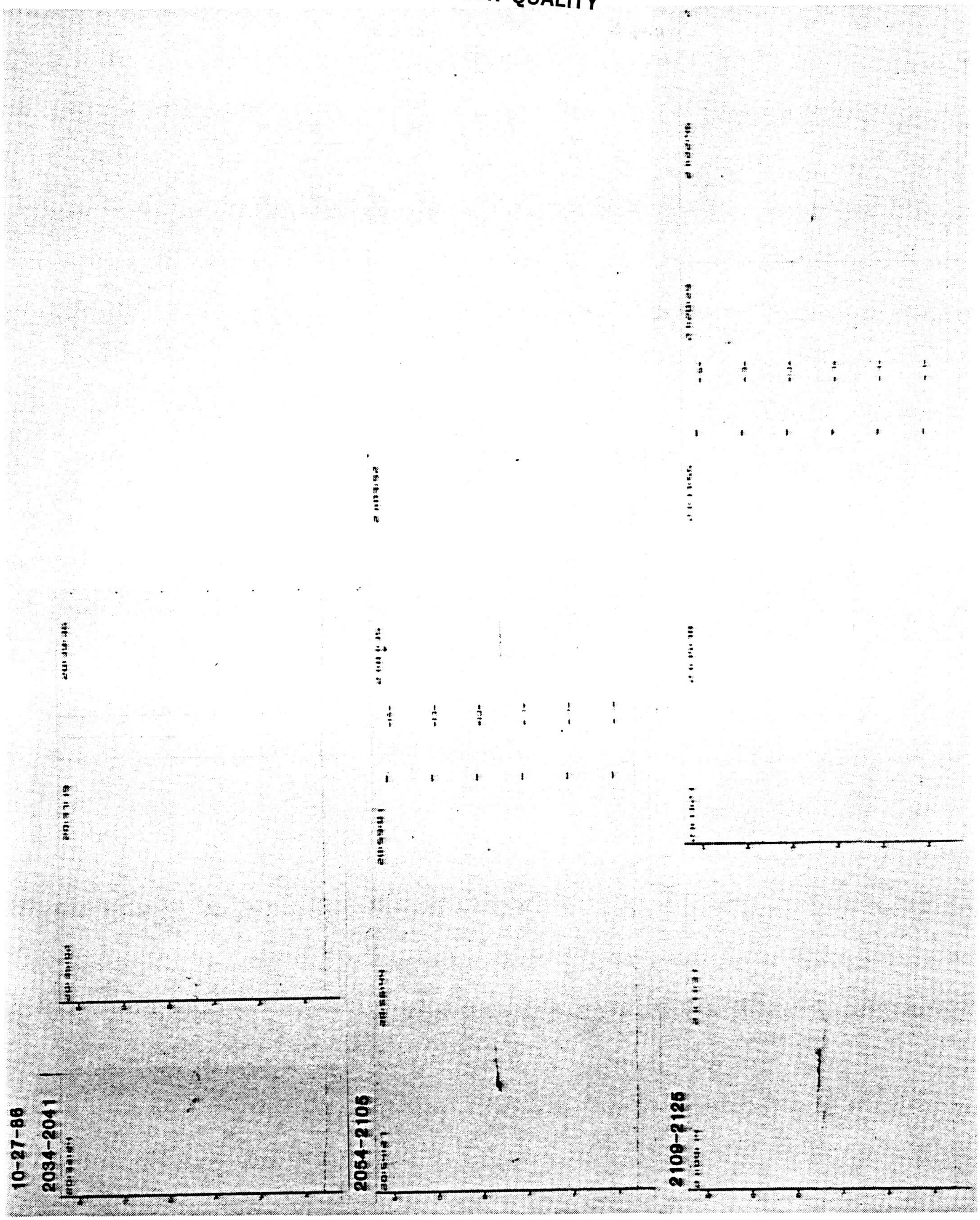
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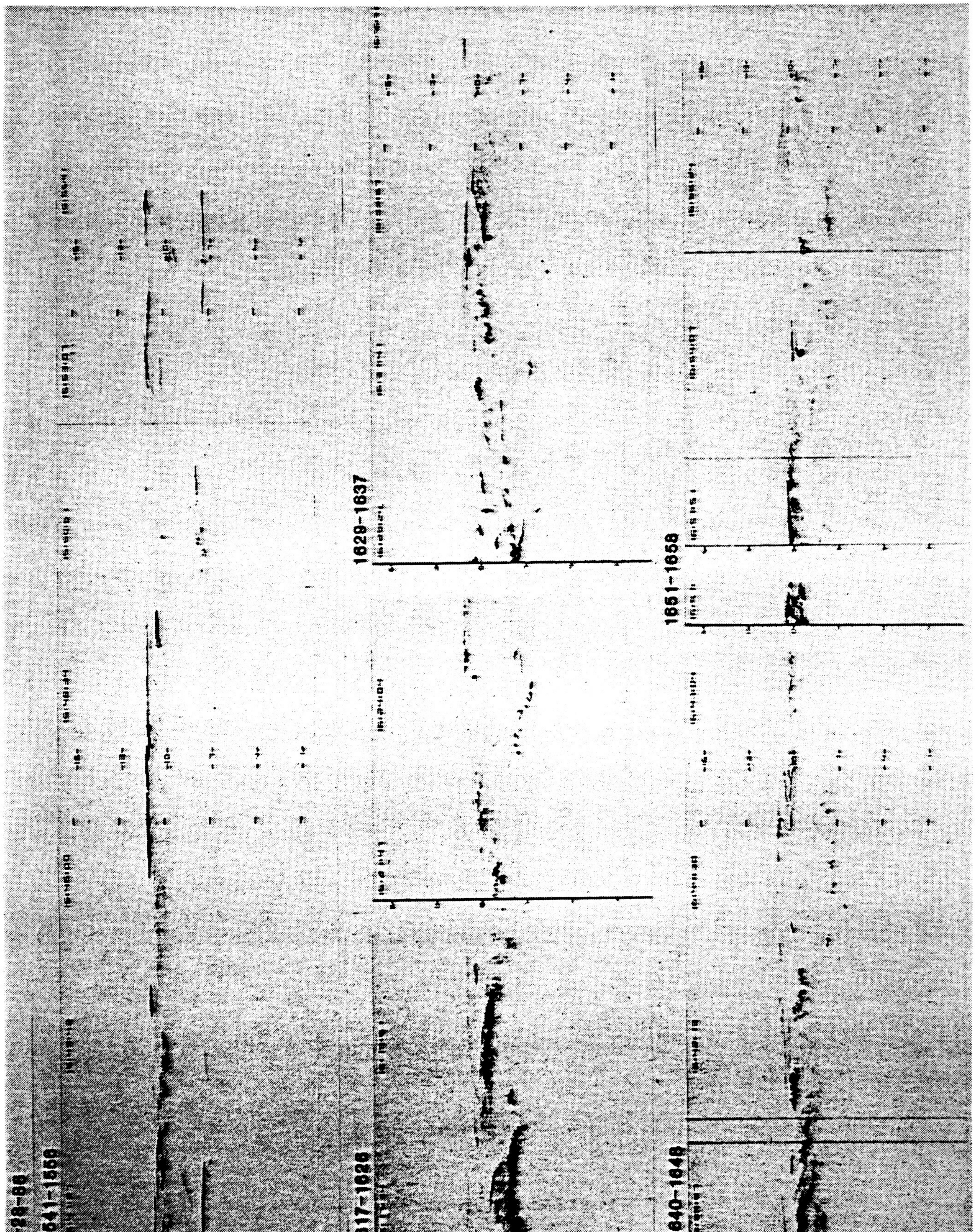
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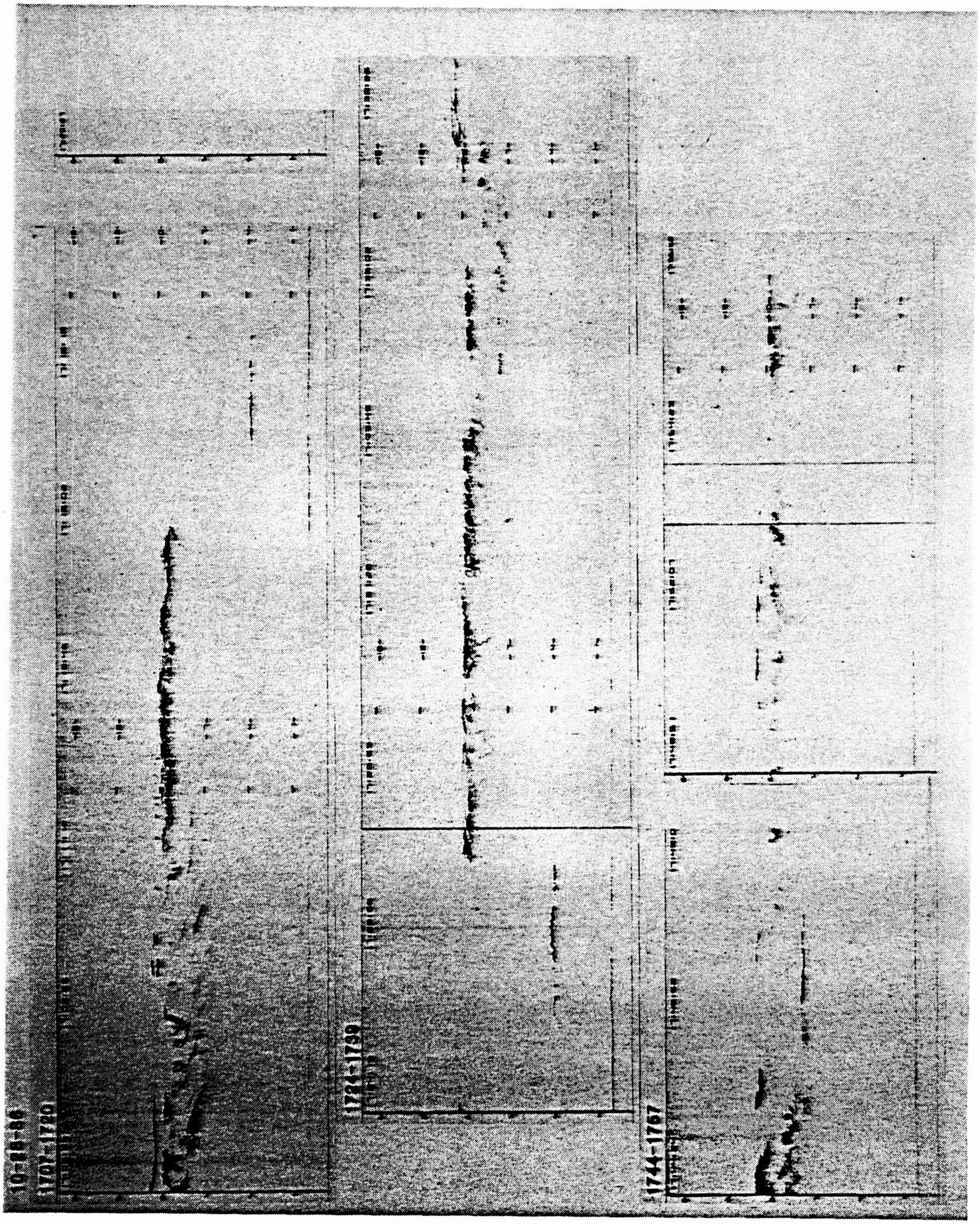

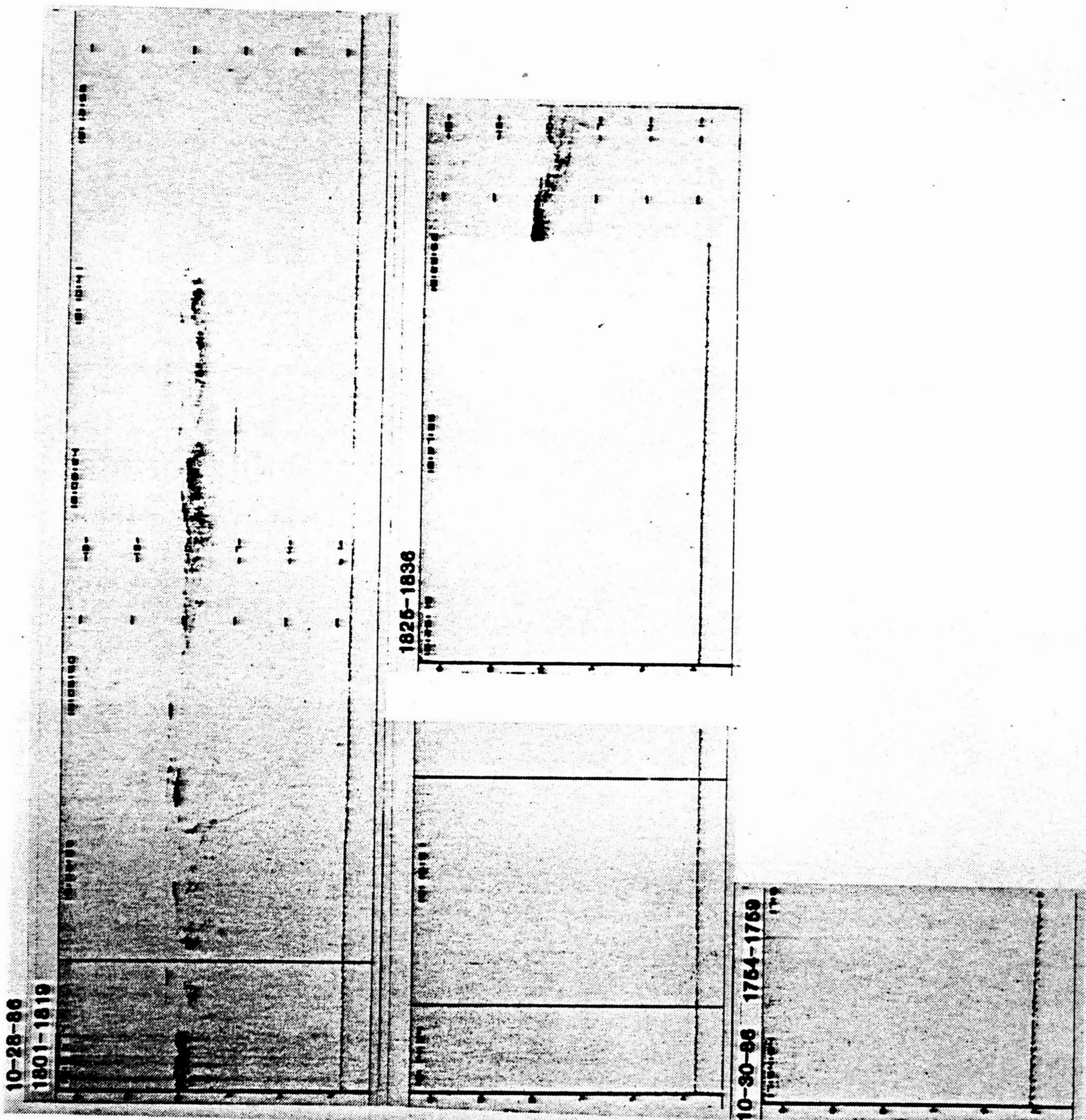
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10-30-86
1754-1759

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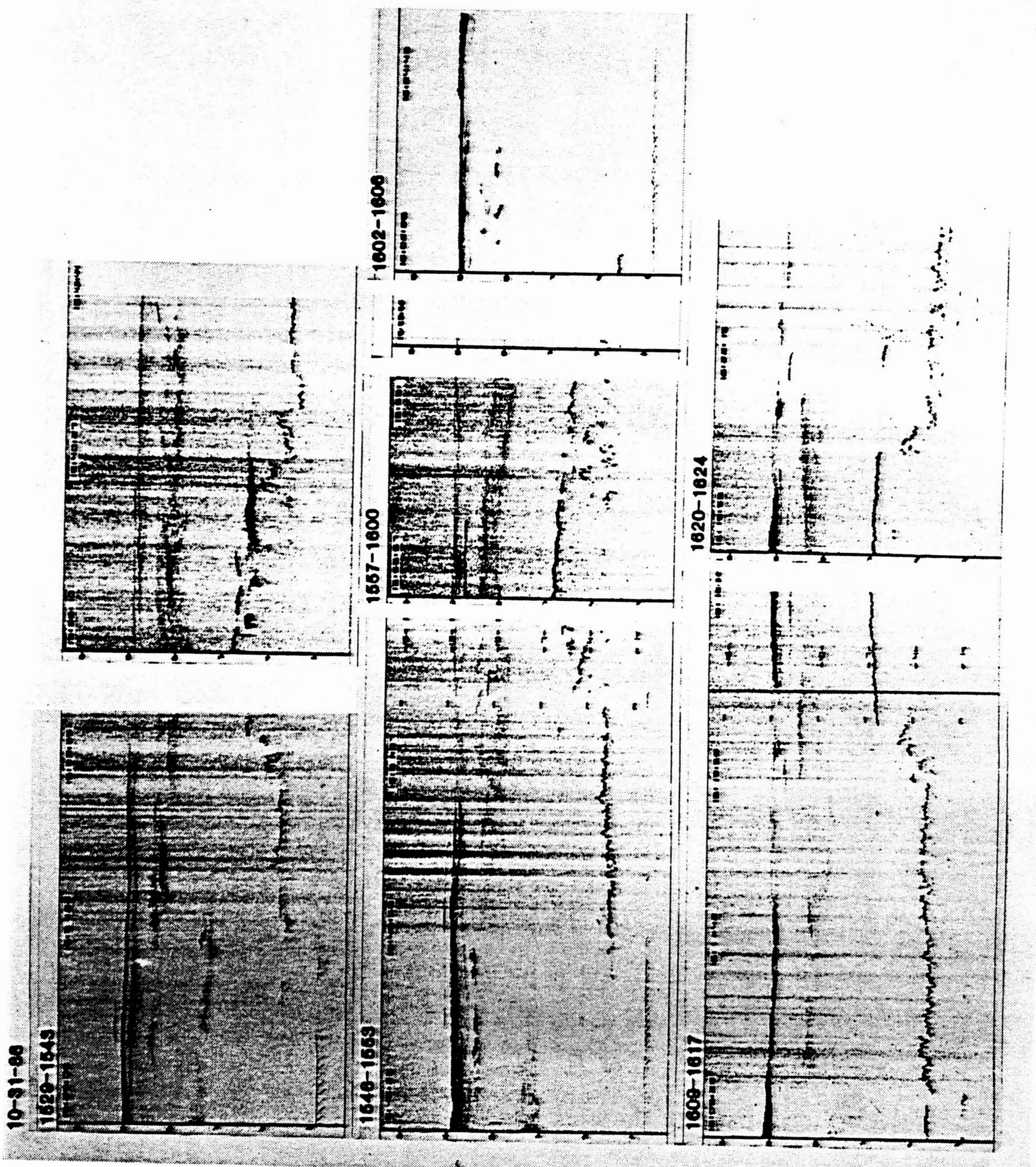

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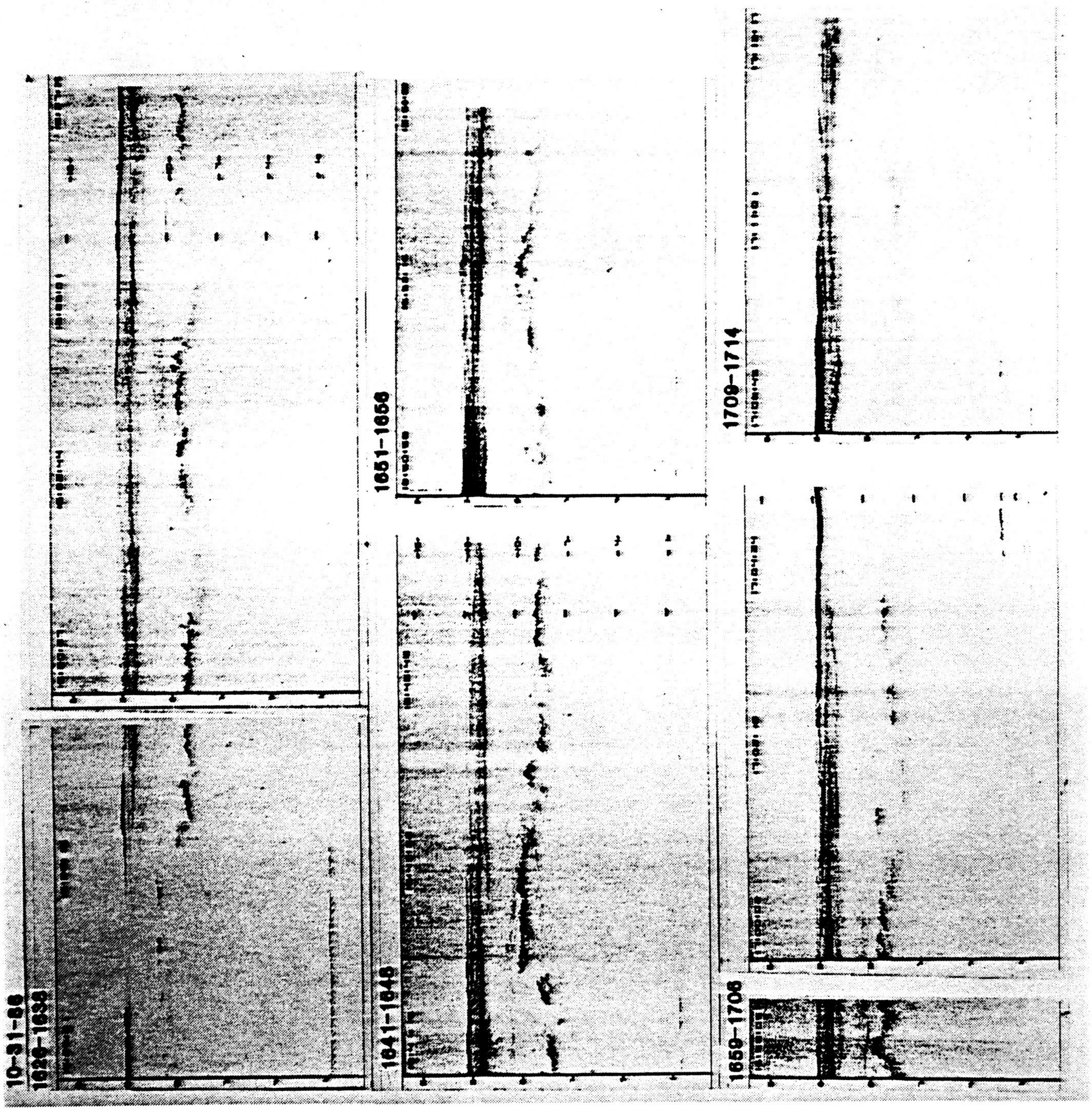

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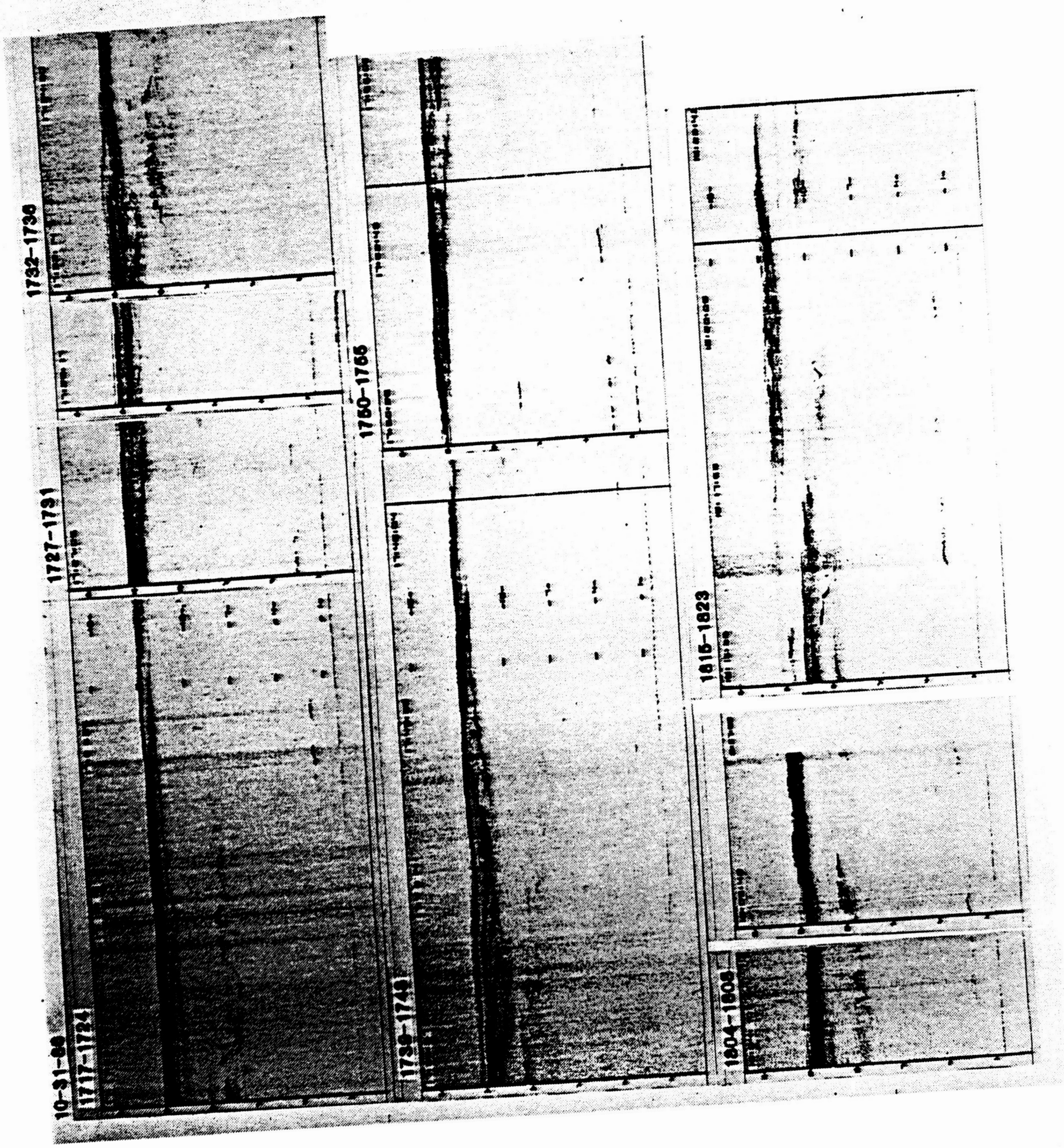

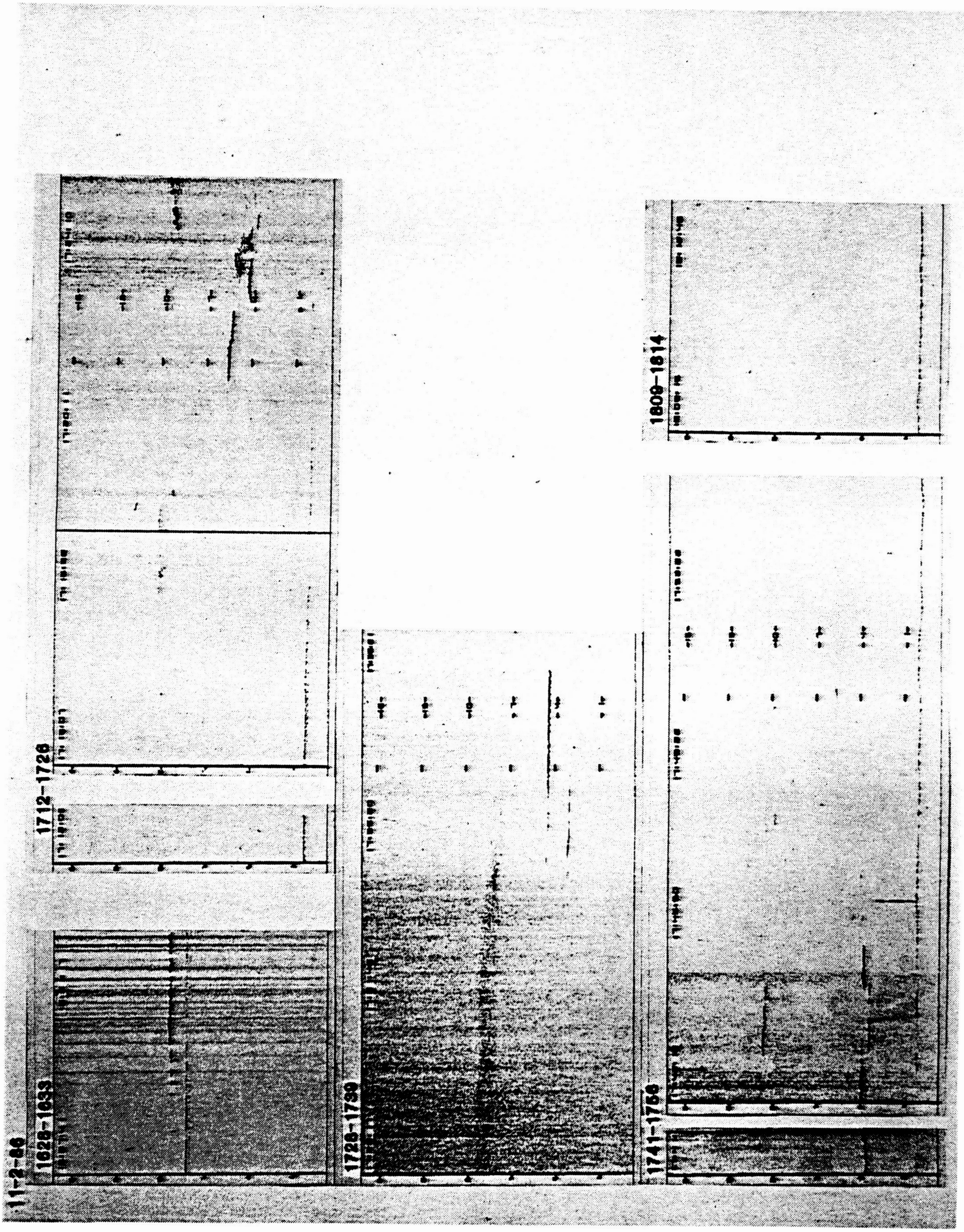

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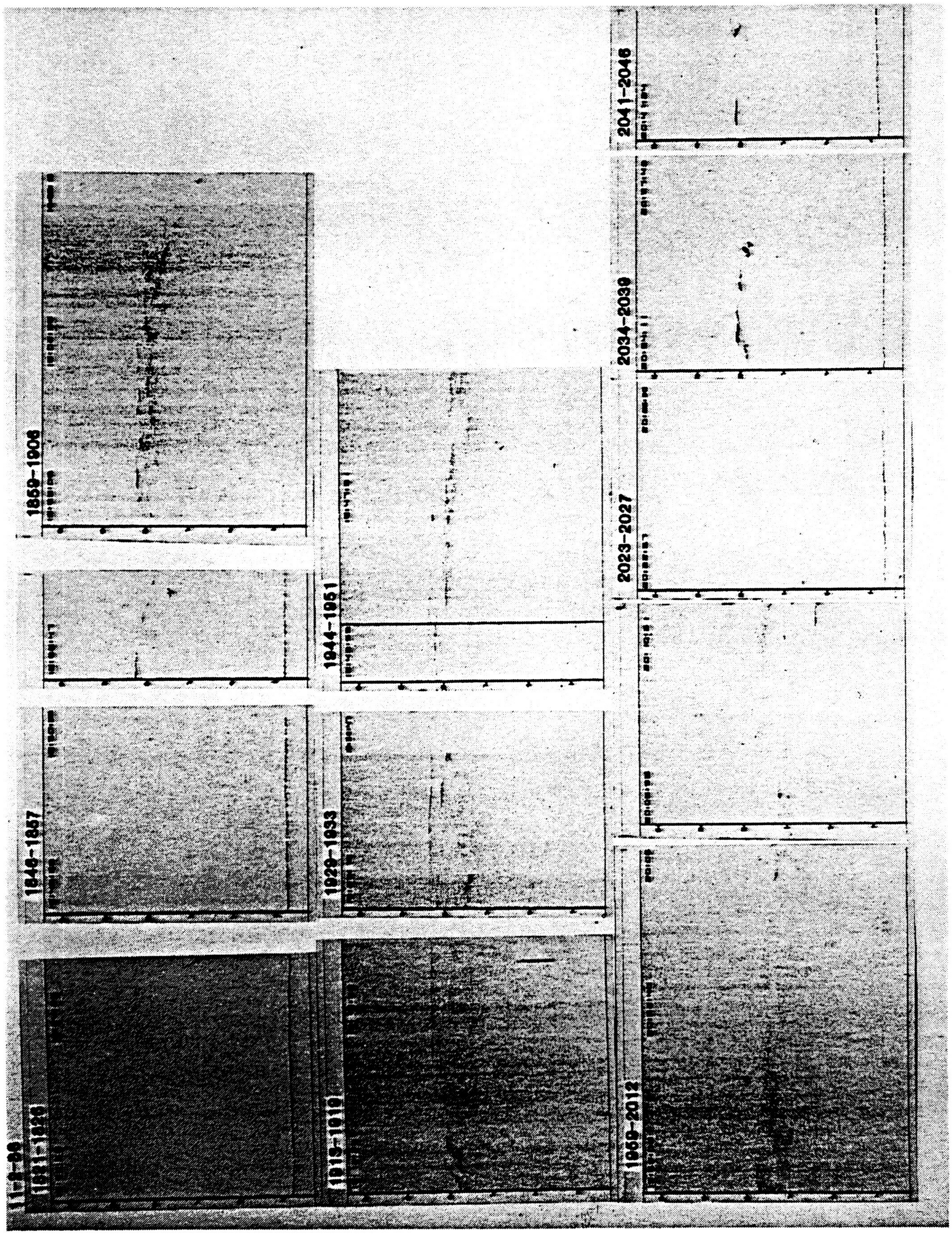
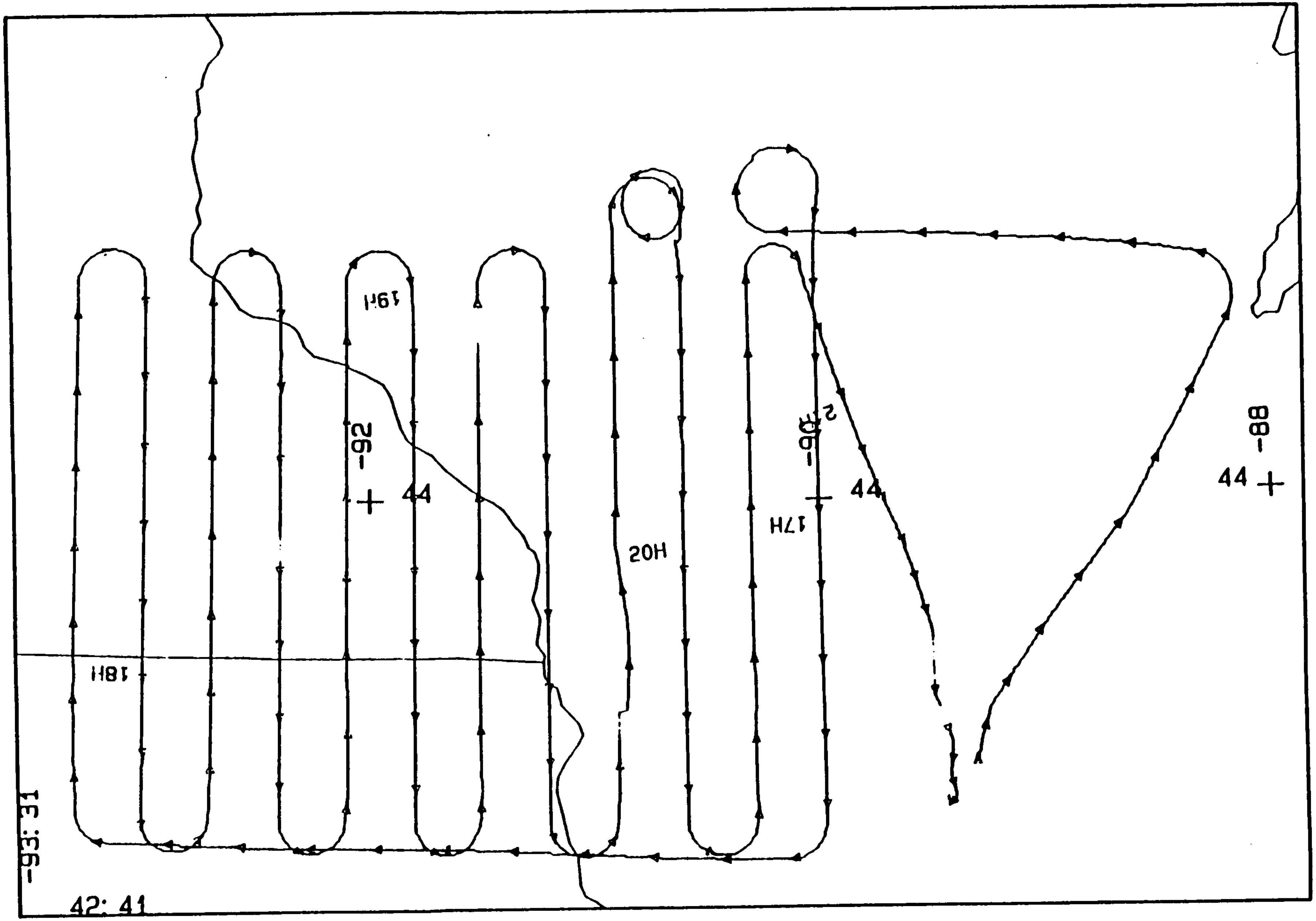


B. Location Maps:

The following location maps show date, time, and the geographic route of the NASA ER-2 aircraft for the eleven dates covered. (Note navigation data was not available for October 19 and 21, so simple maps based on pilot's logs were substituted):



WISCONSIN FIRE FLIGHT 87-006 13 OCTOBER 1986 A/C 706

OVERLAY FOR XCUSA LAMBERT CONFORMAL PROJECTION: SP1 = 42.5 SP2 = 44.7 CM = -90.7 ROTATED BY 0.0

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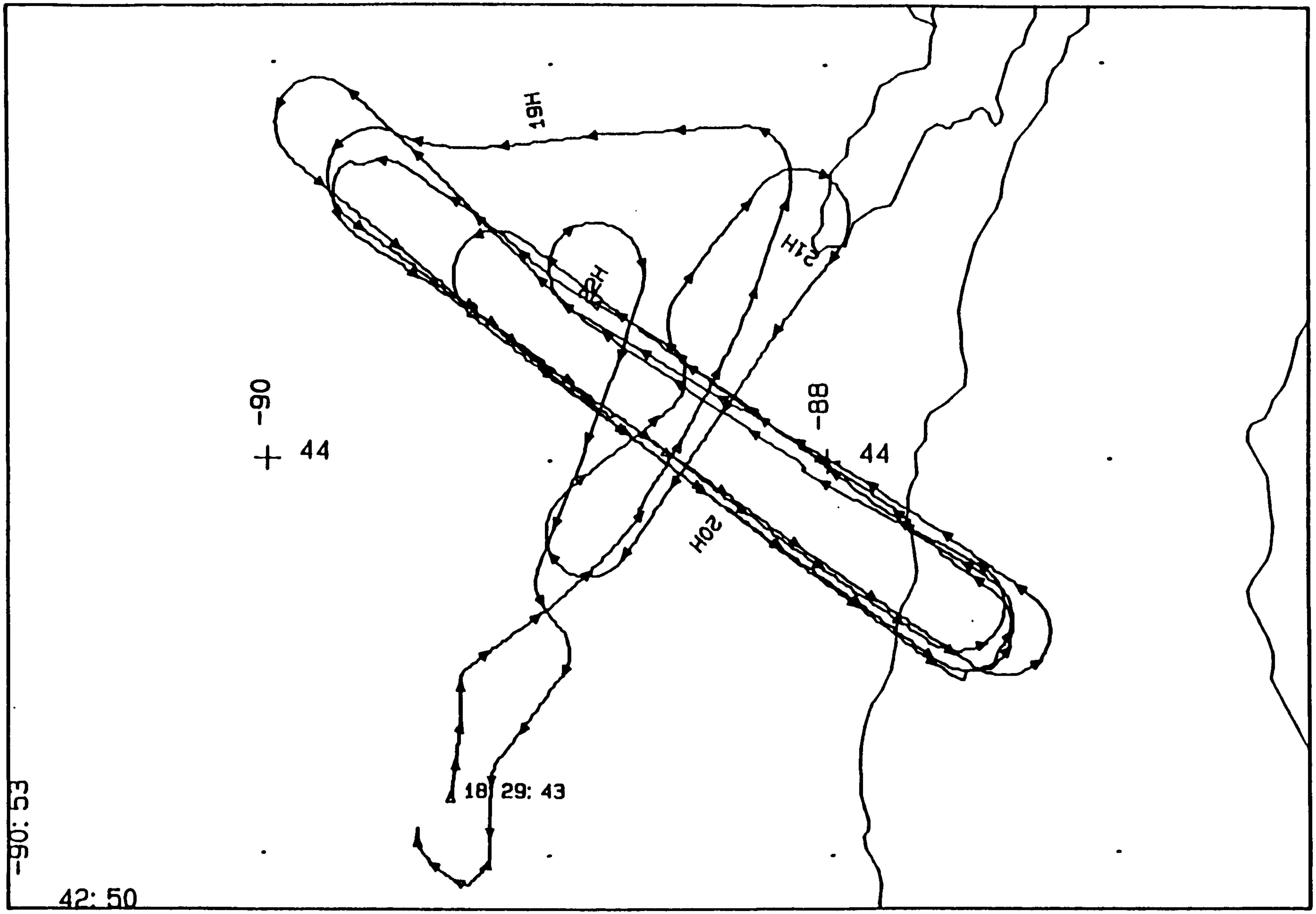

FLIGHT 87-007 DATE 10/15/86 A/C 706

OVERLAY FOR XCUSA ROTATED BY 0.0

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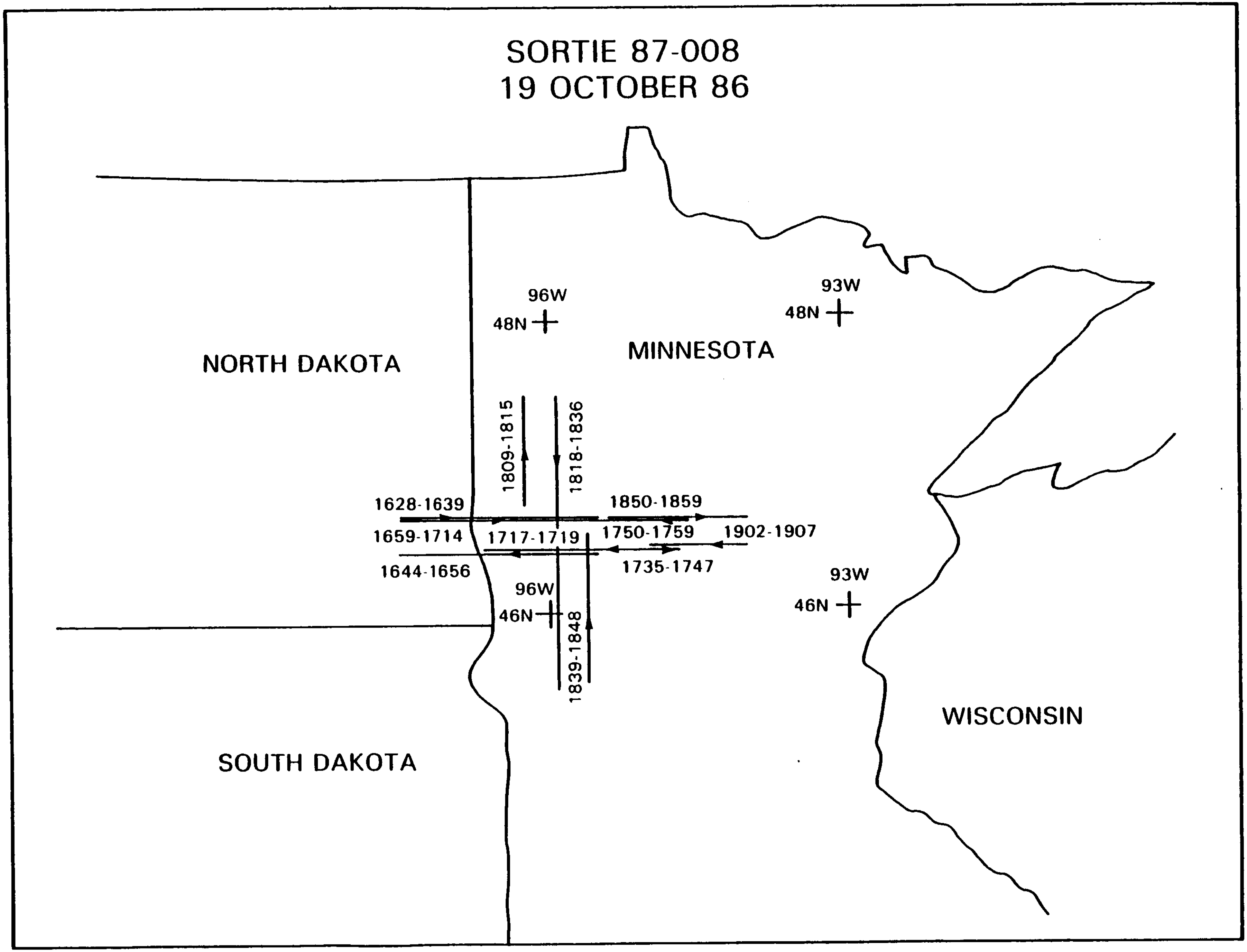
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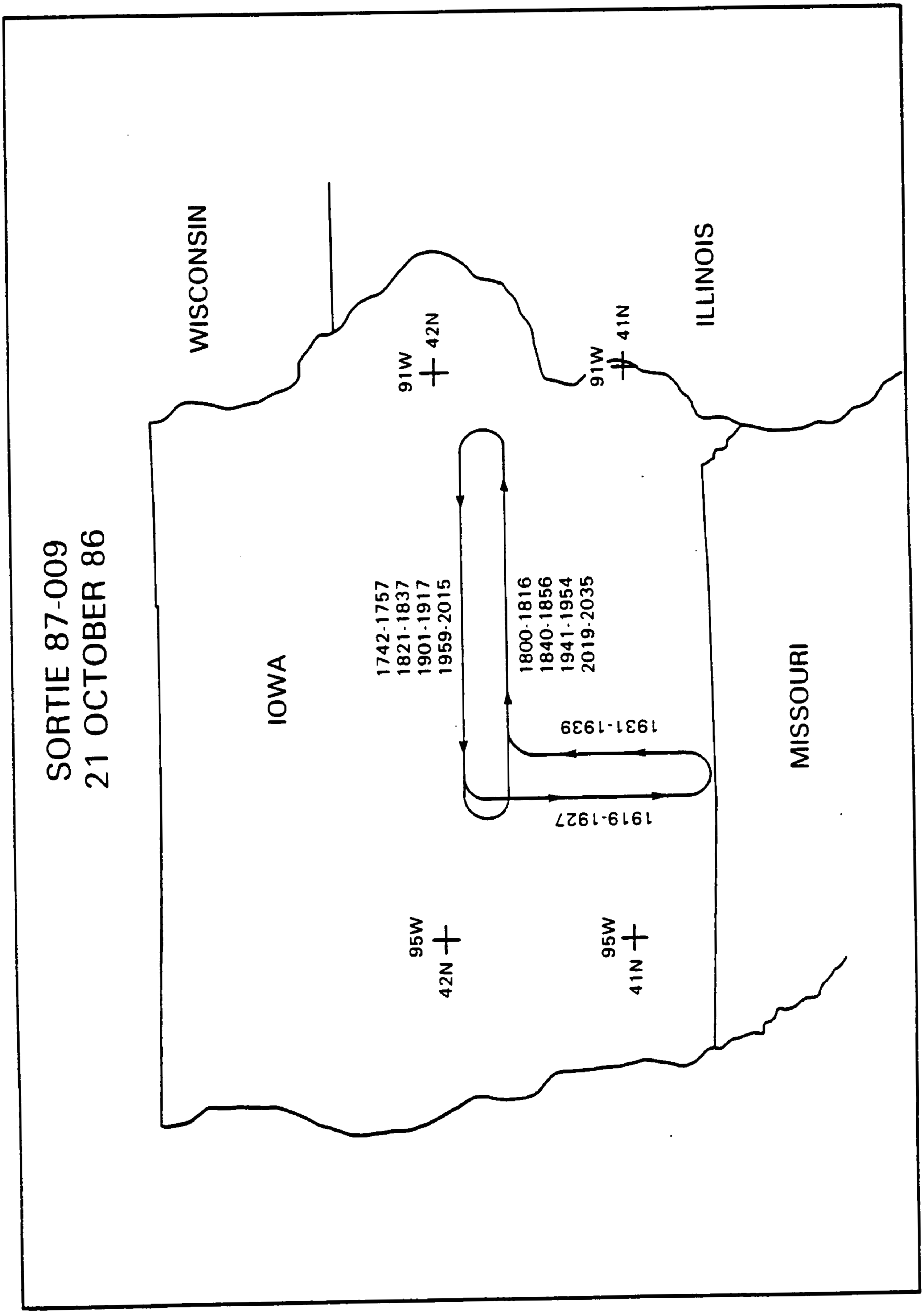
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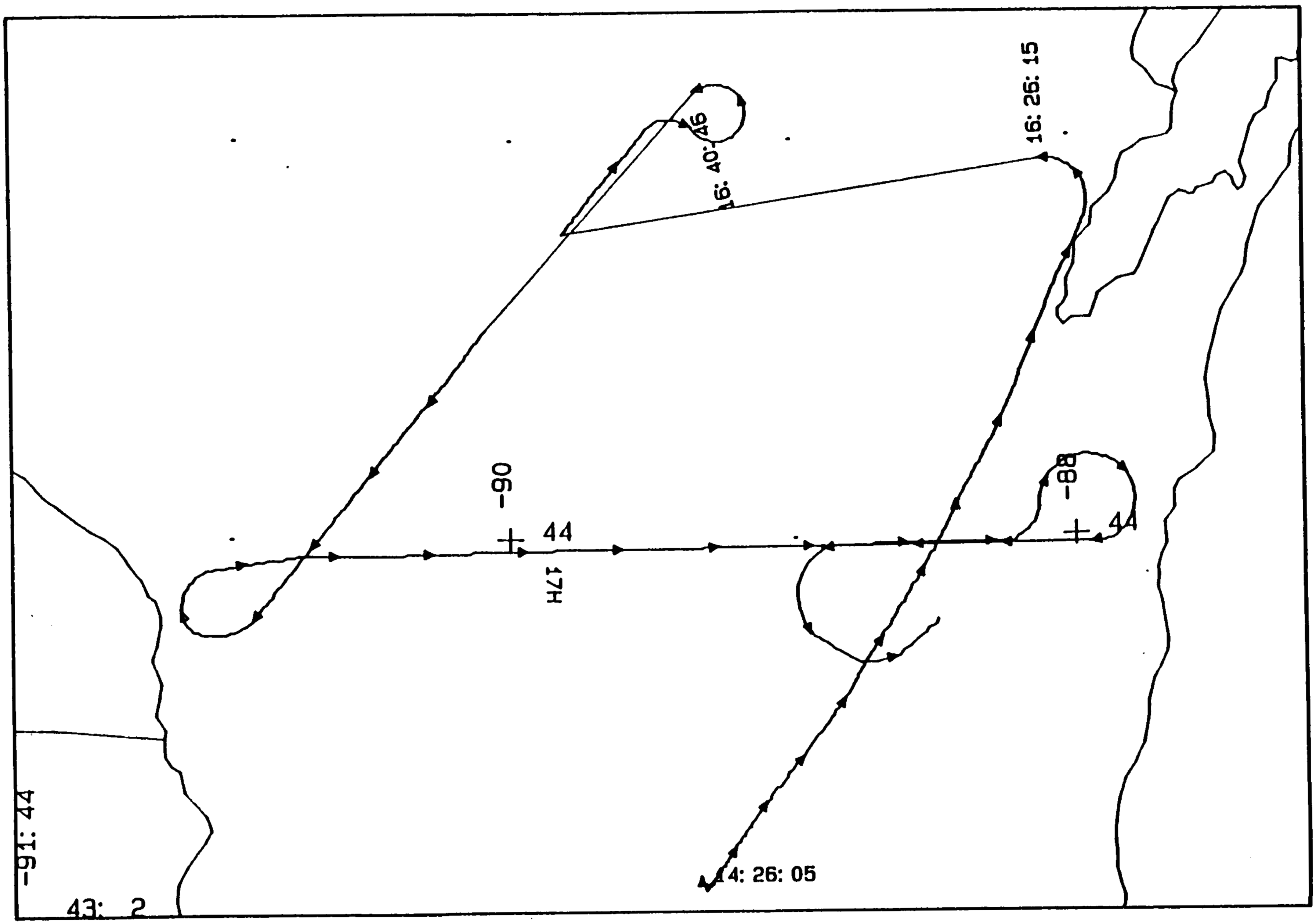
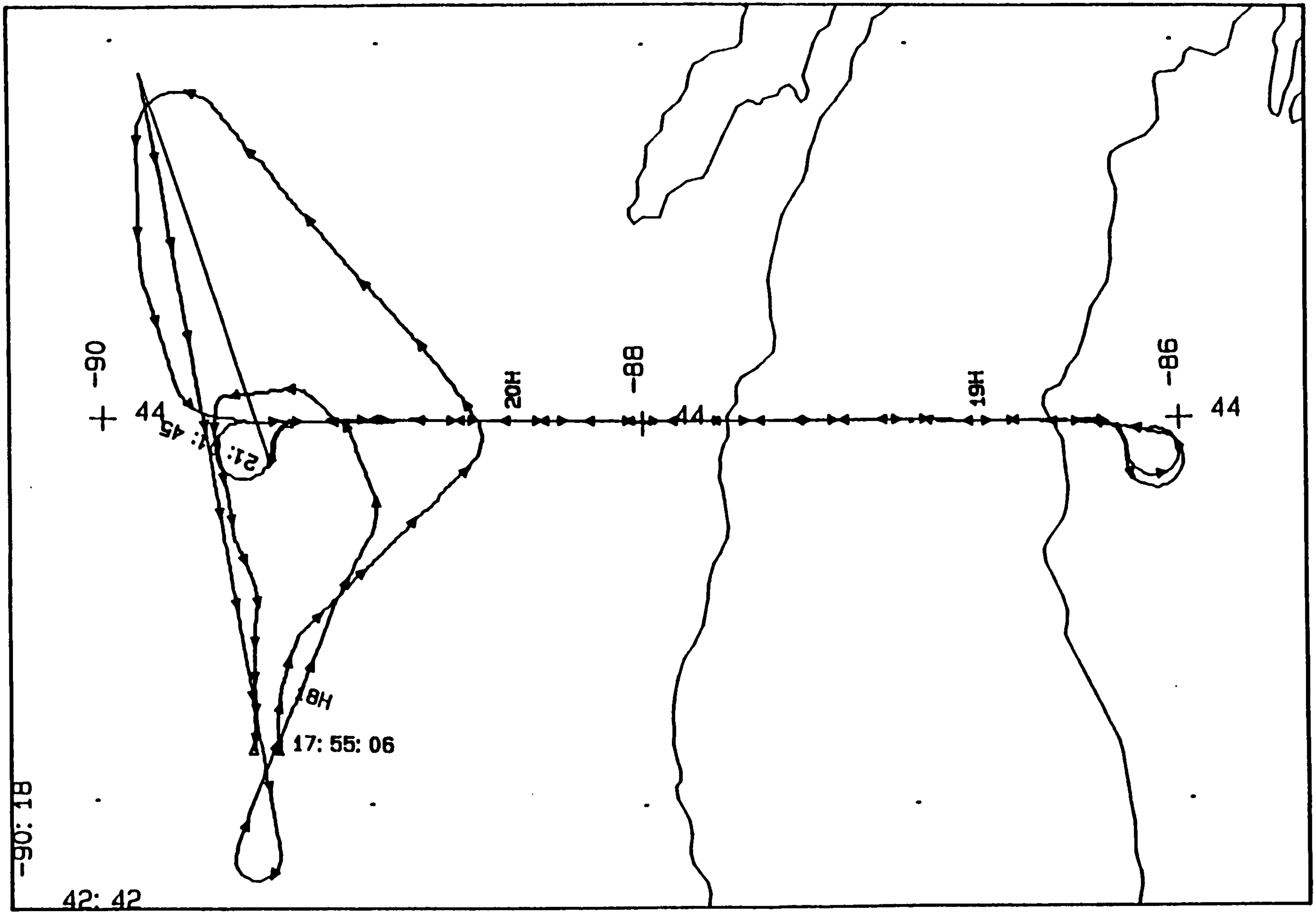
1919-1927



FLIGHT 87-010 DATE 10/22/86 A/C 706

OVERLAY FOR %CUSA ROTATED BY 0.0

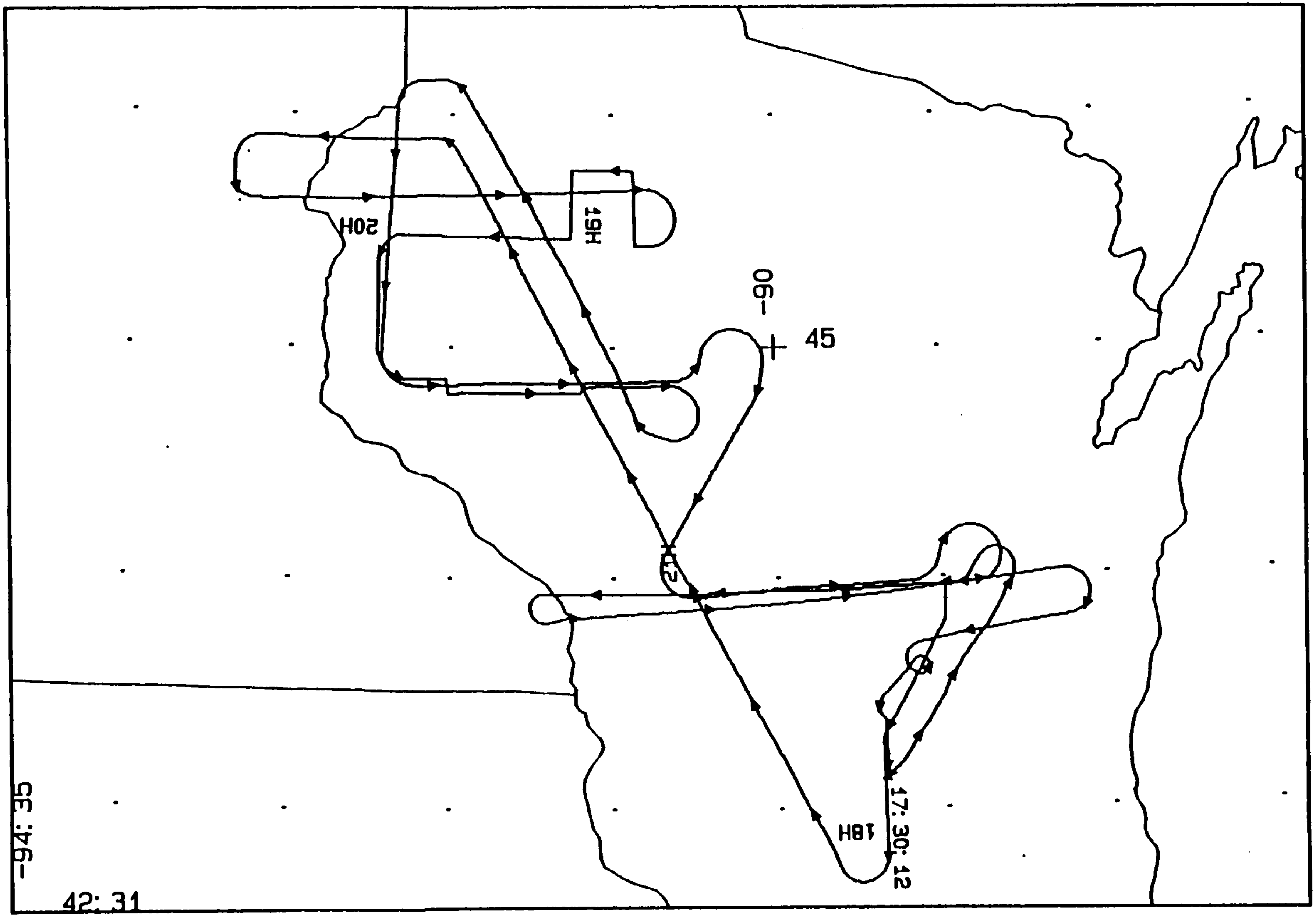
14: 26: 00 TO 17: 28: 02 UT SCALE = 1: 1.52E+06 TIME TICS EVERY 2.00 MINUTES



FLIGHT 87-011 DATE 10/24/86 A/C 706

OVERLAY FOR XCUSA ROTATED BY 0.0

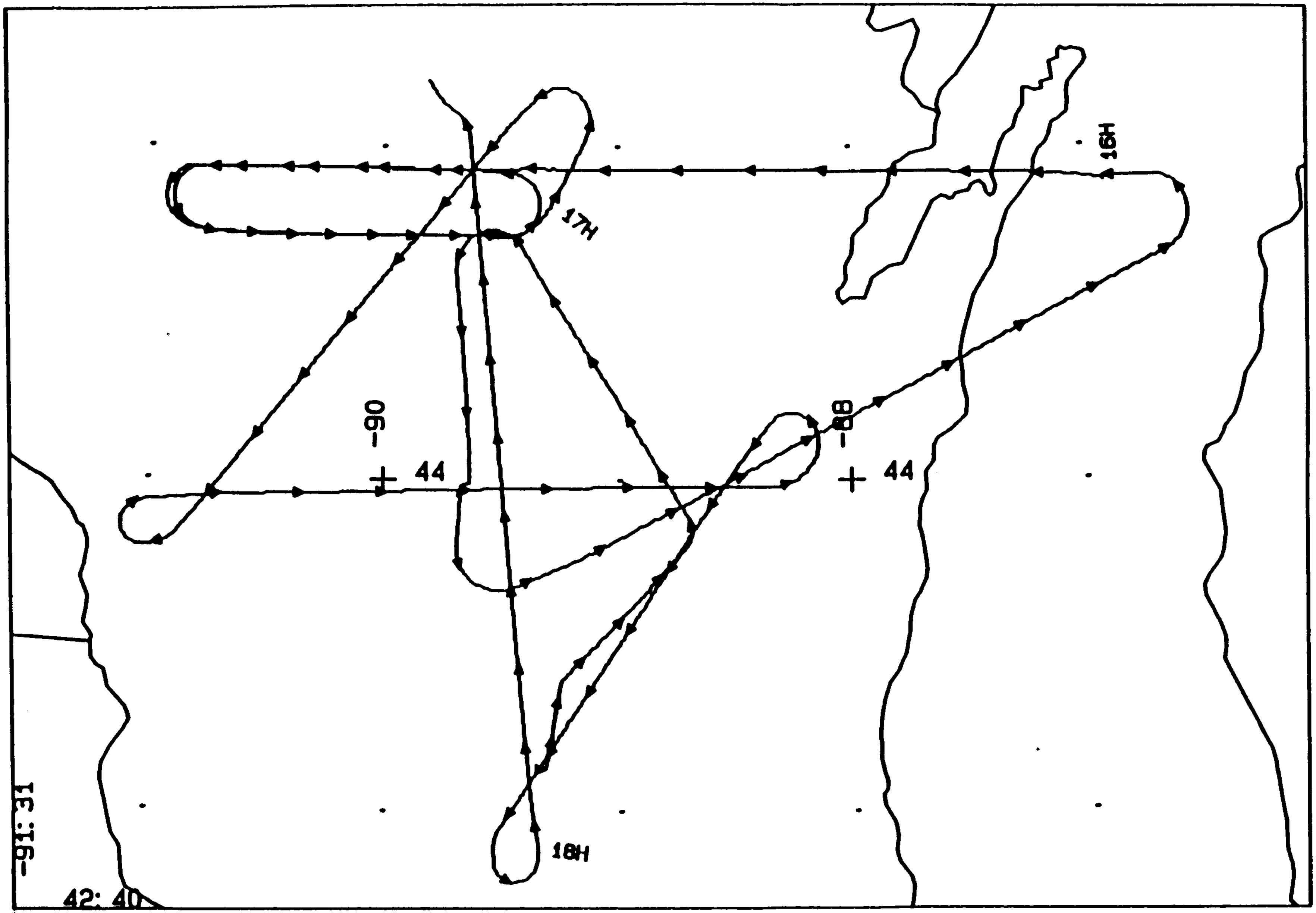
17: 55: 01 TO 21: 59: 57 UT SCALE = 1: 1.60E+06 TIME TICS EVERY 2.00 MINUTES



FLIGHT 87-012 DATE 10/27/86 A/C 706

OVERLAY FOR %CUSA ROTATED BY 0.0

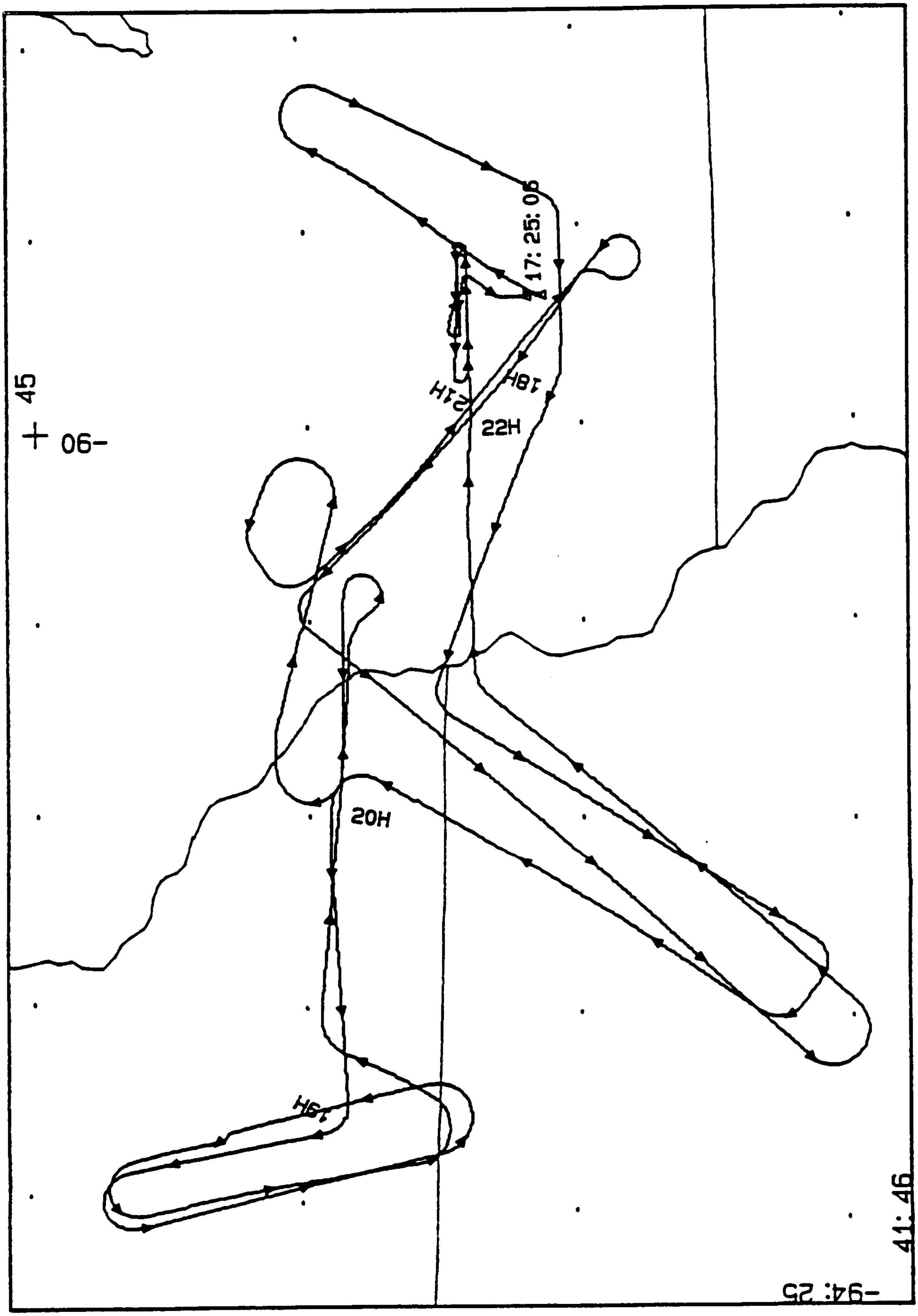
17: 30: 07 TO 21: 57: 11 UT SCALE = 1: 2.62E+06 TIME TICS EVERY 5.00 MINUTES



WISCONSIN - FIRE FLIGHT 87-013 10/28/86 A/C 706

OVERLAY FOR XCUSA LAMBERT CONFORMAL PROJECTION: SP1 = 42.4 SP2 = 44.8 CM = -88.8 ROTATED BY 0.0

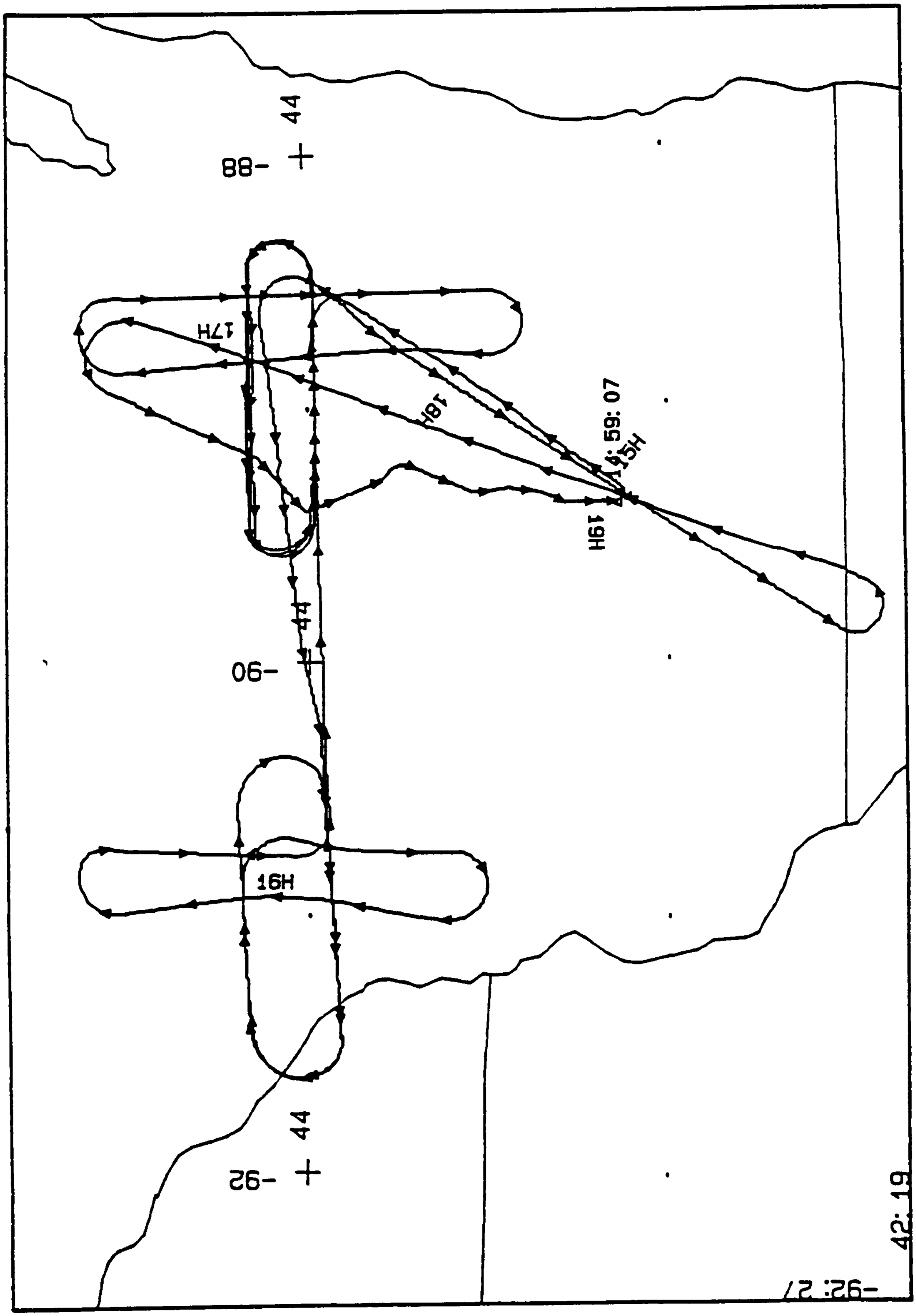
15:02:27 TO 18:21:21 UT SCALE = 1:1.83E+06 TIME TICS EVERY 2.00 MINUTES



FLIGHT 87-014 DATE 10/30/86 A/C 706

OVERLAY FOR XCUSA ROTATED BY 0.0

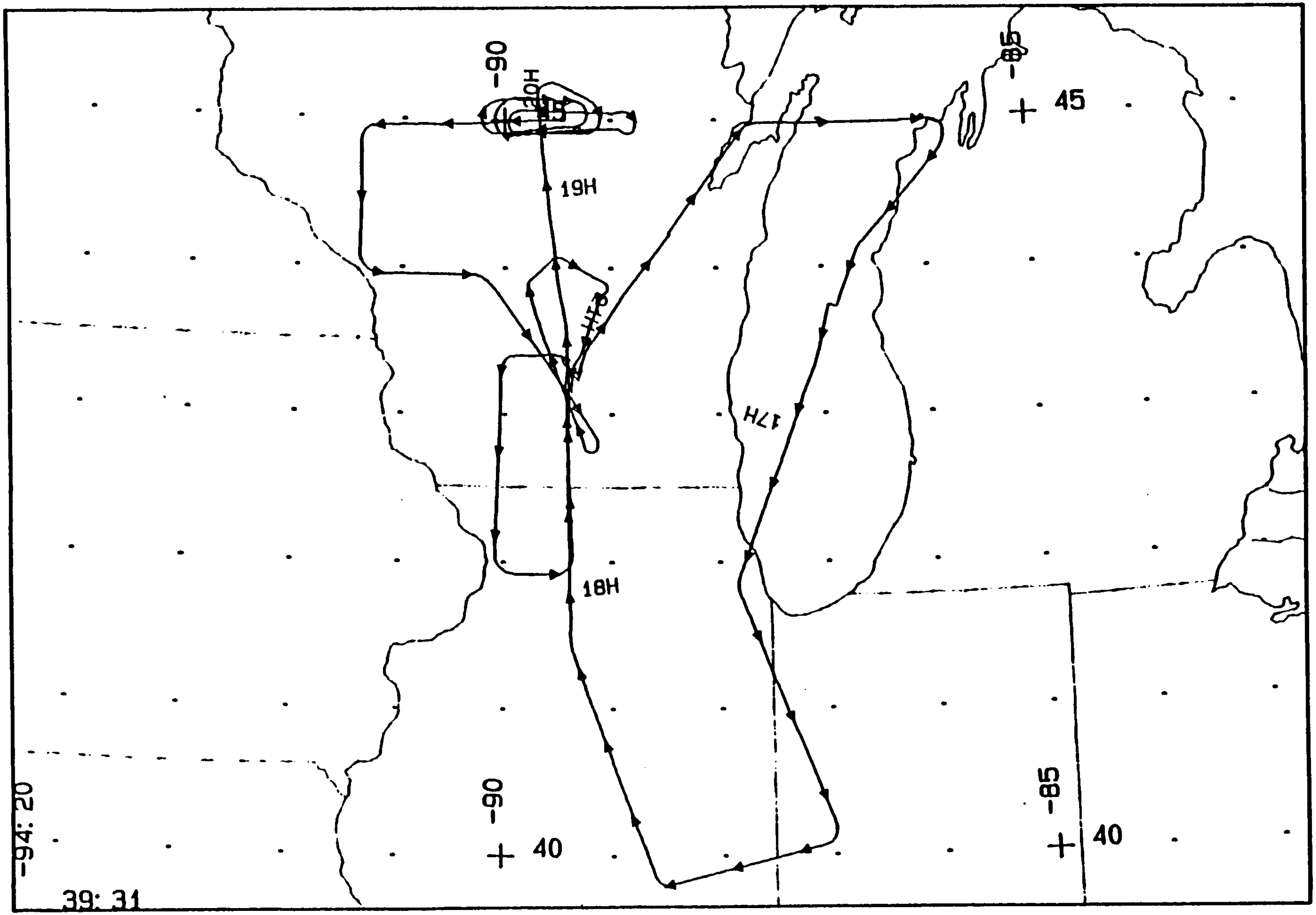
17:25:01 TO 22:59:54 UT SCALE = 1:2.22E+06 TIME TICS EVERY 5.00 MINUTES



FLIGHT 87-015 DATE 10/31/86 A/C 706

OVERLAY FOR XCUSA ROTATED BY 0.0

14: 59: 02 TO 19: 05: 57 UT SCALE = 1: 1.69E+06 TIME TICS EVERY 2.00 MINUTES



WISCONSIN FIRE FLIGHT 87-016 2 NOVEMBER 1986 A/C 706

OVERLAY FOR XCUSA LAMBERT CONFORMAL PROJECTION: SP1 = 38.9 SP2 = 44.3 CM = -88.6 ROTATED BY 0.0

16: 03: 28 TO 21: 17: 10 UT SCALE = 1: 4.09E+06 TIME TICS EVERY 5.00 MINUTES

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15. Supplementary Notes

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16. Abstract

A description of the ER-2 lidar data characteristics and available products, plus flight times and locations are presented for the FIRE cirrus experiment of October 13 through November 2, 1986. The CALS airborne lidar was flown for this experiment on the NASA ER-2 high altitude aircraft. The primary objectives of the CALS observations were to intensively measure cirrus cloud top height and structure for basic cirrus studies and for validation of satellite cloud retrievals.

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